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Progress in Materials Manufacturing, and Energy Systems



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Ranjan Kumar & Arnab Das

**Progress in Materials, Manufacturing,
and Energy Systems**

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Progress in Materials Manufacturing, and Energy Systems

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Preface

In an era defined by rapid technological transformation and interdisciplinary convergence, engineering research continues to be the cornerstone of innovation and societal progress. **Progress in Materials, Manufacturing, and Energy Systems** presents a curated collection of scholarly work that reflects the dynamic landscape of modern engineering. This volume encapsulates recent advances across diverse domains, including mechanical systems, materials development, data-driven modeling, smart manufacturing, and sustainable engineering practices.

The chapters in this book underscore the breadth and depth of ongoing research efforts aimed at addressing real-world engineering challenges. From novel fabrication methods and surface engineering techniques to nanotechnology, the contributions reflect both theoretical rigor and practical relevance. Emphasis has been placed on emerging applications that bridge traditional boundaries—integrating mechanics, computation, automation, and sustainability.

This compilation serves as a vital resource for researchers, practitioners, academicians, and students who aspire to stay abreast of contemporary trends and transformative technologies in engineering. Each chapter not only contributes to academic discourse but also opens new pathways for industrial innovation and interdisciplinary exploration.

We are deeply grateful to the contributing authors for their commitment and insightful contributions. Special thanks to Swami Vivekananda University, Kolkata, for its continuous encouragement and institutional support. We also extend our appreciation to the editorial and review teams for their meticulous efforts in upholding the academic integrity of this publication.

It is our sincere hope that this book inspires further research, fosters meaningful collaboration, and fuels innovation in engineering applications for years to come.

***Dr. Ranjan Kumar
Dr. Arnab Das***

Acknowledgement

We extend our heartfelt gratitude to Swami Vivekananda University, Kolkata, India, for their steadfast support and encouragement in the development of Progress in Materials, Manufacturing, and Energy Systems. The university's unwavering commitment to academic excellence, research advancement, and interdisciplinary learning has been a driving force behind the realization of this volume.

We are particularly thankful for the intellectually stimulating environment, cutting-edge research infrastructure, and collaborative ethos fostered by the institution. Swami Vivekananda University's focus on nurturing innovation across diverse engineering disciplines has enabled the convergence of valuable research insights presented in this book.

Our sincere appreciation goes to the esteemed external reviewers for their thoughtful evaluations and constructive feedback. Their diligence and scholarly expertise have played an essential role in ensuring the academic integrity and quality of this publication.

We also extend our deep thanks to all contributing authors, researchers, and members of the editorial team. Their dedication, persistence, and scholarly contributions have brought this collection to life. It is our hope that this book serves as a meaningful addition to the field of engineering and inspires continued inquiry, innovation, and collaboration.

With sincere gratitude,

Dr. Ranjan Kumar
Dr. Arnab Das

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1

Experimental Investigation of Dual-Fuel Hydrogen-Diesel Combustion in Compression Ignition Engines

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Abstract

Compression ignition (CI) engines benefit from dual-fuel hydrogen-diesel strategies because they lead to both cleaner and more efficient combustion operations. This research analyzes how engine performance interacts with emission levels and combustion behavior in dual-fuel operations with hydrogen as the secondary fuel and diesel as the primary fuel. A complete experimental system was established to collect data about engine functioning along with emission patterns and combustion variables. The tested hydrogen-diesel dual-fuel combustion showed its capability for lowering greenhouse gas emission levels and boosting thermal efficiency while resolving NO_x emission problems and engine-knocking issues.

Introduction

Researchers conduct studies on alternative fuel technologies for internal combustion engines because society needs sustainable and environmentally friendly energy systems worldwide. Hydrogen qualifies as an attractive secondary fuel choice for CI engine dual-fuel systems because of its high energy capacity and complete carbon dioxide emission neutrality. The flame propagation speed of hydrogen enables lean mixtures in addition to diesel primary fuel stability which leads to thermal efficiency enhancements and lower emissions outcomes. The authors conducted experimental work to determine both the technical potential and obstacles associated with dual-fuel burners utilizing hydrogen and diesel in CI engines. A comprehensive

evaluation exists for the performance characteristics of dual-fuel hydrogen-diesel CI engine systems. A research investigation concentrates on recording both greenhouse gas and NO_x outputs. The study examines combustion characteristics while investigating effective knock-control methods. Efforts towards alternative fuel technologies in internal combustion engines. Hydrogen, with its high energy content and zero-carbon emissions, emerges as a promising secondary fuel for dual-fuel CI engine operations. Diesel, as a primary fuel, ensures stable combustion, while hydrogen's rapid flame propagation facilitates leaner mixtures, leading to potentially improved thermal efficiency and reduced emissions. This paper presents an experimental investigation to evaluate the feasibility and challenges of dual-fuel hydrogen-diesel combustion in CI engines.

Objectives

- To analyze the performance characteristics of a dual-fuel hydrogen-diesel CI engine.
- To study the emission characteristics, particularly focusing on greenhouse gases and NO_x.
- To evaluate the combustion behavior and identify the knock mitigation strategies.

Literature Review

The research by Verhelst et al. (2019) demonstrated how dual-fuel applications using hydrogen produce lower CO₂ emissions because of the fuel's fast diffusivity and low ignition needs. The study by Saravanan et al. (2021) showed that hydrogen improves engine combustion efficiency through extensive flammability ranges yet warns about pre-ignition and knock potential issues during operations. Karim et al. (2018) through their experimental and computational work demonstrated that dual-fuel hydrogen-diesel engines reach performance-emission equilibrium with precise hydrogen injection timing management. Wang et al. (2022) conducted recent research which demonstrated that partial diesel replacement by hydrogen decreased particulate matter (PM) pollution while increasing nitrogen oxide (NO_x) emissions thus requiring advanced after-treatment solutions. Thus CO₂ emissions when used in dual-fuel modes, attributing this to its high diffusivity and low ignition energy.

- Saravanan et al. (2021) noted that hydrogen can enhance combustion efficiency due to its wide flammability limits but cautioned against knock and pre-ignition risks.

Dual-Fuel Combustion Studies

- A computational and experimental study by Karim et al. (2018) emphasized that dual-fuel hydrogen-diesel engines can achieve a balance between

performance and emissions but require precise control of hydrogen injection timing.

- Recent experiments by Wang et al. (2022) suggested that partial substitution of diesel with hydrogen significantly reduces particulate matter (PM) emissions but increases NO_x emissions, necessitating effective after-treatment systems.

Challenges and Mitigation

- NO_x Emissions: Kumar et al. (2020) presented exhaust gas recirculation (EGR) as an alternative method to manage NO_x formation in hydrogen combustion processes.
- Knock Mitigation: The study by Kim et al. (2021) identified hydrogen flow rate optimization in addition to late injection strategies for knock mitigation.

Methodology

Experimental Setup

The researchers redesigned a single-cylinder four-stroke CI engine to run under dual-fuel conditions. Key parameters included:

- Engine specifications: 500 cc displacement, 17.5:1 compression ratio.
- Hydrogen injection system: The system used an electronically activated injector for controller operation.
- Diesel fuel injection: Conventional high-pressure injection system.
- Measurement tools: A test setup utilized in-cylinder pressure sensors and exhaust gas analyzers and high-speed cameras for combustion observation.

Test Matrix

- Hydrogen energy share (HES): Varied from 0% to 40%.
- Load conditions: Low (25%), medium (50%), and high (75%) engine load.
- Injection timings: Scientists optimized hydrogen injection schedule to operate within a crank angle span from -30° to -10°.

Data Acquisition

The researchers evaluated brake thermal efficiency (BTE) and specific fuel consumption (SFC) as performance measurement indicators. The measurement system recorded a complete emission profile for CO₂ along with CO and HC pollutants in addition to measuring NO_x and PM emissions. Computational tools performed analysis of combustion metrics including pressure rise rate and heat release rate.

Results and Discussion

- **Performance Characteristics**
 - BTE improved by up to 15% with a 30% hydrogen energy share (HES), attributed to the high energy density of hydrogen and more effective combustion.
 - SFC decreased as the hydrogen fraction increased, indicating better fuel efficiency.
- **Emission Characteristics**
 - CO₂ and CO Emissions: CO₂ emissions dropped by 25% due to hydrogen's carbon-free nature. CO emissions also saw a reduction thanks to enhanced oxidation when hydrogen was present.
 - NOx Emissions: NOx emissions increased with higher HES, consistent with the higher combustion temperatures associated with hydrogen.
 - Particulate Matter: PM emissions decreased by as much as 40% because hydrogen combustion does not produce carbon.
- **Combustion Behavior**
 - The maximum cylinder pressure increased with a higher HES, leading to improved thermal efficiency but also a greater risk of knock.
 - The rate of heat release showed faster combustion phases with hydrogen, necessitating precise timing control.
 - Late hydrogen injection and lean mixtures were implemented to mitigate knock tendencies.

Conclusion

This research demonstrated that dual-fuel hydrogen-diesel combustion can enhance engine performance and reduce carbon emissions in compression ignition (CI) engines. Key findings include:

- Improved thermal efficiency and lower CO₂ emissions with increased hydrogen substitution.
- The issues of NOx emissions and knock tendencies require targeted solutions, such as exhaust gas recirculation (EGR) and optimized injection techniques.
- Future research should focus on advanced control systems and after-treatment technologies to fully realize the potential of hydrogen-diesel dual-fuel engines.

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2

Metal Matrix Composites by Nano-Particles: A Review

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Abstract

Metal Matrix Composites (MMCs) reinforced with nano-particles represent a breakthrough in material science, offering remarkable improvements in mechanical, thermal, and tribological properties. These composites, combining metallic matrices with nano-scale reinforcements, are pivotal in applications across aerospace, automotive, and biomedical sectors. This review delves into the synthesis techniques, the influence of nano-particles on properties, and their diverse applications. Additionally, it highlights challenges such as dispersion uniformity and interfacial bonding, providing insights into future research directions. By analyzing recent advancements, this article aims to guide the development and utilization of nano-particle reinforced MMCs for high-performance applications.

Keywords: Metal Matrix Composites, Nano-Particles, Synthesis Techniques, Applications.

Introduction

Metal Matrix Composites (MMCs) reinforced with nano-particles have emerged as a promising class of materials that bridge the gap between metals and ceramics. These composites represent a significant evolution in material science, where the

integration of nano-scale reinforcements into metal matrices results in materials with unprecedented mechanical, thermal, and tribological properties. The primary advantage of nano-particle reinforcements lies in their high surface area-to-volume ratio, which enhances the interfacial interactions with the matrix and contributes to improved load transfer, thermal stability, and wear resistance (Gupta & Kumar, 2021; Zhou et al., 2021). Furthermore, the uniform dispersion of nano-particles within the metal matrix can lead to grain refinement and the mitigation of defects, further augmenting the composite's overall performance (Patil et al., 2020).

MMCs reinforced with nano-particles have found applications in various industries, including aerospace, automotive, electronics, and biomedical sectors. For instance, in the aerospace industry, these materials offer a high strength-to-weight ratio and excellent thermal stability, making them ideal for structural components exposed to extreme environments (Johnson et al., 2023). Similarly, the automotive industry leverages the wear resistance and lightweight properties of these composites to enhance vehicle efficiency and durability (Mehta & Agarwal, 2022). In the biomedical field, the biocompatibility and corrosion resistance of nano-reinforced MMCs have made them suitable for implants and prosthetics (Singh & Kumar, 2020).

Despite their immense potential, the development and application of nano-particle reinforced MMCs are not without challenges. Key issues include achieving uniform dispersion of nano-particles, ensuring strong interfacial bonding, and addressing the high costs associated with advanced processing techniques (Sharma & Singh, 2018). Furthermore, scalability remains a critical hurdle as researchers transition from laboratory-scale experiments to industrial-scale production (Zhao et al., 2022).

This review aims to provide a comprehensive overview of the current state of nano-particle reinforced MMCs, focusing on their synthesis methods, enhanced properties, and diverse applications. By analyzing recent advancements and identifying gaps in knowledge, this article seeks to guide future research and development efforts in this promising field.

Synthesis Methods

- **Powder Metallurgy**

Powder metallurgy is a prevalent method for fabricating MMCs reinforced with nano-particles. It involves blending metal powders with nano-scale reinforcements, followed by compaction and sintering. The uniform distribution of nano-particles is critical for achieving desired properties. Advanced techniques like mechanical alloying and ultrasonic mixing are employed to address agglomeration issues (Gupta & Kumar, 2021).

- **Stir Casting**

Stir casting is a cost-effective and scalable fabrication technique. Nano-particles are introduced into a molten metal matrix, and vigorous stirring ensures their dispersion. However, achieving a homogeneous distribution remains a challenge, often mitigated through pre-treatment of reinforcements (Wang et al., 2020).

- **In-situ Synthesis**

In-situ synthesis involves generating nano-reinforcements within the metal matrix during processing. This method ensures superior bonding between the matrix and reinforcements, enhancing composite properties. Common techniques include chemical vapor deposition and reactive gas injection (Zhang & Li, 2019).

- **Friction Stir Processing**

Friction stir processing (FSP) is an advanced technique used to incorporate nano-particles into the surface layer of metal matrices. It provides precise control over reinforcement distribution and microstructural refinement (Reddy et al., 2022).

- **Additive Manufacturing**

Additive manufacturing, including selective laser melting and electron beam melting, has been explored for fabricating MMCs. This approach offers unparalleled design flexibility and control over microstructure but is limited by high costs and process complexity (Zhao et al., 2022).

Mechanical Properties

- **Strength and Hardness**

Nano-particles enhance the strength and hardness of MMCs through mechanisms such as grain boundary strengthening, load transfer, and dispersion strengthening. Improved dislocation density around reinforcements contributes to these properties (Zhou et al., 2021).

- **Wear Resistance**

Nano-reinforced MMCs exhibit superior wear resistance due to the high hardness and uniform distribution of nano-particles. This makes them ideal for applications in abrasive environments (Sharma & Singh, 2018).

- **Ductility**

While nano-reinforcements often reduce ductility, optimizing matrix composition and processing parameters can mitigate this issue, ensuring a balance between strength and ductility (Patil et al., 2020).

Applications

- **Aerospace**

Nano-particle reinforced MMCs are extensively utilized in aerospace components such as turbine blades and structural panels. Their high strength-to-weight ratio and thermal stability are key advantages (Johnson et al., 2023).

- **Automotive**

In the automotive industry, these composites are used in engine components, brake discs, and transmission parts. Their wear resistance and lightweight characteristics contribute to enhanced fuel efficiency and durability (Mehta & Agarwal, 2022).

- **Biomedical**

Biocompatible MMCs with nano-reinforcements are employed in implants, prosthetics, and dental applications. Their superior mechanical properties and corrosion resistance are critical for success in biomedical environments (Singh & Kumar, 2020).

- **Electronics**

In electronic applications, nano-particle reinforced MMCs serve as heat sinks and substrates due to their excellent thermal conductivity and stability under high operating temperatures (Chen et al., 2021).

Challenges

Despite their potential, MMCs reinforced with nano-particles face challenges such as:

- **Dispersion Uniformity:** Achieving a homogeneous distribution of nano-particles within the matrix remains a major obstacle.
- **Interfacial Bonding:** Strong bonding between the matrix and nano-particles is essential for property enhancement.
- **Cost and Scalability:** The high cost of nano-particles and advanced processing techniques limits their industrial adoption.
- **Environmental Stability:** Ensuring stability under extreme environmental conditions is a critical research area.

Future Prospects

The future of nano-particle reinforced MMCs lies in developing cost-effective synthesis methods, enhancing interfacial bonding, and exploring novel applications. Advancements in computational modeling and characterization techniques will play a pivotal role in overcoming current limitations. Computational simulations can provide deeper insights into material behavior, enabling optimized designs and processes. Meanwhile, the integration of machine learning algorithms into material design

workflows can accelerate the discovery of new nano-particle and matrix combinations (Zhao et al., 2022).

Sustainability will also be a crucial factor, with researchers focusing on environmentally friendly fabrication methods and recycling strategies to reduce waste and energy consumption. Additionally, interdisciplinary collaborations between material scientists, engineers, and industry stakeholders are expected to bridge the gap between laboratory research and large-scale production (Sharma & Singh, 2018). The exploration of hybrid composites, incorporating multiple types of nano-reinforcements, presents another promising avenue for achieving tailored properties for specific applications. As these advancements unfold, nano-particle reinforced MMCs are poised to redefine performance benchmarks across numerous industries.

Conclusion

Nano-particle reinforced Metal Matrix Composites have revolutionized material science with their exceptional properties and versatile applications. These materials offer a unique combination of strength, thermal stability, and wear resistance, making them indispensable in aerospace, automotive, biomedical, and electronic sectors. While challenges such as dispersion uniformity, interfacial bonding, and cost remain, ongoing research is actively addressing these issues. The integration of advanced fabrication techniques, computational modelling, and sustainable practices is expected to significantly enhance the feasibility and scalability of these composites (Gupta & Kumar, 2021; Zhou et al., 2021).

The road ahead for nano-particle reinforced MMCs is both exciting and challenging. As researchers continue to innovate and industry stakeholders invest in this transformative technology, these composites are likely to emerge as cornerstone materials in high-performance applications. By combining the strengths of metals and nano-reinforcements, they hold the potential to push the boundaries of what materials can achieve in the 21st century and beyond.

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3

Monitoring Rotational Accuracy of High-Speed Spindles: A Review

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Abstract

The rotational accuracy of high-speed spindles is critical to the performance of modern manufacturing processes. This paper reviews the methodologies, instrumentation, and advancements in monitoring spindle rotational accuracy, emphasizing real-time diagnostic tools and sensor technologies. Current trends in precision manufacturing necessitate robust systems for evaluating spindle performance, ensuring high quality and productivity. Challenges and future directions are also discussed.

Keywords: High Speed Spindle, Rotational Accuracy, Laser Diode, Quadrant Sensor.

Introduction

High-speed spindles are central to various machining processes, determining the precision and efficiency of operations such as milling, grinding, and drilling. Rotational accuracy, a key performance metric, directly influences surface quality, tool wear, and machining tolerances. Fig. 1 shows a high speed spindle for the application of high speed micro milling operation. Continuous monitoring of spindle rotational accuracy is thus essential to maintain optimal performance.



Fig. 1: High Speed Spindle for High Speed Micro Milling Operation

This review consolidates existing techniques, identifying their strengths, limitations, and applicability to real-world scenarios. Spindles used in advanced manufacturing, such as aerospace and automotive industries, demand stringent accuracy due to tight tolerances (Kakinuma et al., 2015). Monitoring solutions must evolve to meet the increasing complexity and speed of modern machines.

Key Parameters of Rotational Accuracy

Rotational accuracy encompasses several parameters, including:

- **Radial Error Motion:** Deviation in the spindle's rotational axis from its ideal path. This error affects surface roughness and concentricity of machined parts (Schröder et al., 2017).
- **Axial Error Motion:** Variations along the spindle's axis. Axial inaccuracies can result in uneven cuts and excessive tool wear (Kim et al., 2019).
- **Tilt Error Motion:** Angular deviations of the spindle axis. Tilt errors often lead to non-uniform machining and misaligned components (Park et al., 2020).

These errors are quantified using standards such as ISO 230-7 and ASME B89.3.4, ensuring uniformity in measurement practices globally. Advanced diagnostic tools, such as dynamic signal analyzers, have been developed to assess these parameters more effectively (Zhang & Lu, 2021).

Measurement Techniques

- **Contact-Based Methods**

Contact-based techniques, such as the use of capacitive displacement sensors and dial indicators, remain widely used. These methods offer high precision

but are limited by wear and tear and are unsuitable for high-speed environments (Chen et al., 2020). Precision ball bars and spindle analyzers are also utilized for comprehensive error assessment (Johansson et al., 2016). Fig. 2 represents the contact-based monitoring of high speed spindle rotation.



Fig. 2: Contact-Based Method for Monitoring of High Speed Spindle Rotation

- **Non-Contact Methods**

Non-contact methods, including laser interferometry and optical encoders, have gained prominence due to their ability to operate at high speeds. Laser Doppler Vibrometry (LDV), for instance, provides precise measurements of spindle vibrations and deviations (Kumar & Singh, 2019). Optical techniques, such as heterodyne interferometers, have further enhanced the resolution of rotational measurements (Gupta et al., 2018).

- **Advanced Sensor Technologies**

Recent advancements in sensor technology have enabled the use of MEMS-based sensors and fiber Bragg gratings for real-time monitoring. These systems integrate with digital platforms, facilitating predictive maintenance (Zhang et al., 2021). Innovations in piezoelectric sensors have also contributed to improved vibration analysis (Luo et al., 2022). Fig. 3 represents the schematic diagram of a high-speed spindle rotation measurement system using a laser diode and a quadrant sensor.

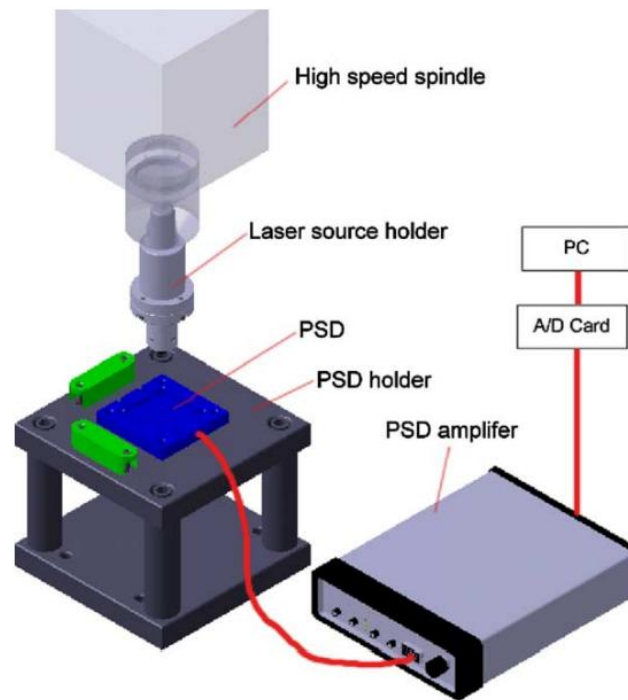


Fig. 3: Schematic Diagram of a High-Speed Spindle Rotation Measurement System Using a Laser Diode and a Quadrant Sensor (Jywe and Chen, 2005)

Real-Time Monitoring Systems

Real-time monitoring systems leverage machine learning algorithms to analyze spindle performance. Data collected from multiple sensors is processed to predict potential failures, enhancing productivity and reducing downtime (Lee et al., 2018). Cloud-based monitoring platforms allow remote diagnostics and data sharing, creating opportunities for collaborative maintenance strategies (Wang & Cheng, 2021).

Integration with Industry 4.0 principles has led to the development of smart spindles equipped with embedded sensors. These systems provide continuous feedback on performance metrics, enabling adaptive control of machining processes (Bajpai et al., 2023).

Challenges in Monitoring Rotational Accuracy

Despite advancements, challenges remain in:

- **Sensor Calibration:** Ensuring consistent performance across different operational conditions. Calibration protocols often require downtime and specialized equipment (Huang et al., 2020).

- **Data Integration:** Combining data from multiple sources without loss of fidelity. Real-time fusion of diverse sensor outputs poses computational challenges (Tan et al., 2021).
- **High-Speed Operation:** Maintaining accuracy at extremely high rotational speeds. High centrifugal forces and thermal effects can degrade sensor performance (He et al., 2022).

Future Directions

Future research should focus on:

- Developing hybrid monitoring systems that combine contact and non-contact methods. These systems could leverage the strengths of both approaches to improve accuracy and reliability (Liu et al., 2023).
- Enhancing the robustness of real-time diagnostic tools using AI and big data analytics. Predictive algorithms should be capable of handling noise and uncertainties in data (Xie et al., 2023).
- Reducing system costs while improving accessibility for small-scale manufacturers. Low-cost sensor solutions and open-source diagnostic tools could democratize precision monitoring (Nguyen & Tran, 2024).

Conclusion

Monitoring the rotational accuracy of high-speed spindles is pivotal for precision manufacturing. While significant progress has been made, ongoing challenges necessitate further innovation in sensor technologies and analytical methods. Collaborative efforts between academia and industry will be essential to achieve these advancements.

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4

Experimental Investigation of Heat Transfer Enhancement in Thermal Systems Using Nanofluids: A Review

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Abstract

The quest for efficient thermal management has driven researchers to explore advanced methods of heat transfer enhancement. This paper presents an experimental study on the use of nanofluids for improving heat transfer performance in thermal systems. Nanofluids, which are engineered by dispersing nanoparticles into base fluids, exhibit superior thermal conductivity and convective heat transfer properties. The research investigates the effects of nanoparticle concentration, fluid flow rate, and heat flux on the thermal performance of a heat exchanger. The results demonstrate significant improvements in heat transfer coefficients, highlighting the potential of nanofluids in modern thermal applications. Challenges related to stability, cost, and environmental impact are also discussed, along with future research directions.

Introduction

Efficient heat transfer is a critical factor in the design and operation of thermal systems across various industries, including power generation, automotive, and electronics cooling. Conventional fluids, such as water, ethylene glycol, and oil, often exhibit limited thermal conductivity, which constrains the performance of heat exchangers and other thermal devices. To address this limitation, researchers have developed nanofluids—a novel class of heat transfer fluids that incorporate nanoparticles to enhance thermal properties.

Nanofluids have garnered significant attention due to their remarkable potential for improving thermal conductivity, heat transfer coefficients, and energy efficiency. The addition of nanoparticles, such as aluminum oxide (Al₂O₃), copper oxide (CuO), and graphene, to base fluids alters their thermophysical properties, enabling enhanced heat transfer performance. However, the practical implementation of nanofluids in thermal systems requires a comprehensive understanding of their behavior under varying operating conditions.

This paper presents an experimental investigation into the heat transfer enhancement capabilities of nanofluids. The study focuses on a shell-and-tube heat exchanger, evaluating the impact of nanoparticle concentration, fluid flow rate, and heat flux on thermal performance. Additionally, the challenges associated with nanofluid stability, cost-effectiveness, and environmental impact are explored to provide a holistic perspective on their viability in real-world applications.

Methodology

The experimental setup consists of a shell-and-tube heat exchanger designed to facilitate the controlled evaluation of heat transfer performance. Key components of the setup include:

- **Heat Exchanger:** A stainless-steel shell-and-tube heat exchanger with an inner tube diameter of 10 mm and a length of 1 m.
- **Nanofluids Preparation:** Nanofluids are prepared by dispersing nanoparticles of aluminum oxide (Al₂O₃) into deionized water. A surfactant is used to ensure stability, and the mixture is subjected to ultrasonication for uniform dispersion.
- **Instrumentation:** Thermocouples, flow meters, and a data acquisition system are employed to monitor and record temperature, flow rate, and heat transfer rates.
- **Operating Conditions:** Experiments are conducted at varying nanoparticle concentrations (0.01% to 0.1% by volume), fluid flow rates (0.5 to 2.5 L/min), and heat flux levels (200 to 600 W/m²).

The experiments involve circulating the nanofluid through the heat exchanger while applying controlled heat flux to the shell side. The thermal performance is assessed by measuring the temperature rise, heat transfer coefficient, and pressure drop across the Heat Exchanger.

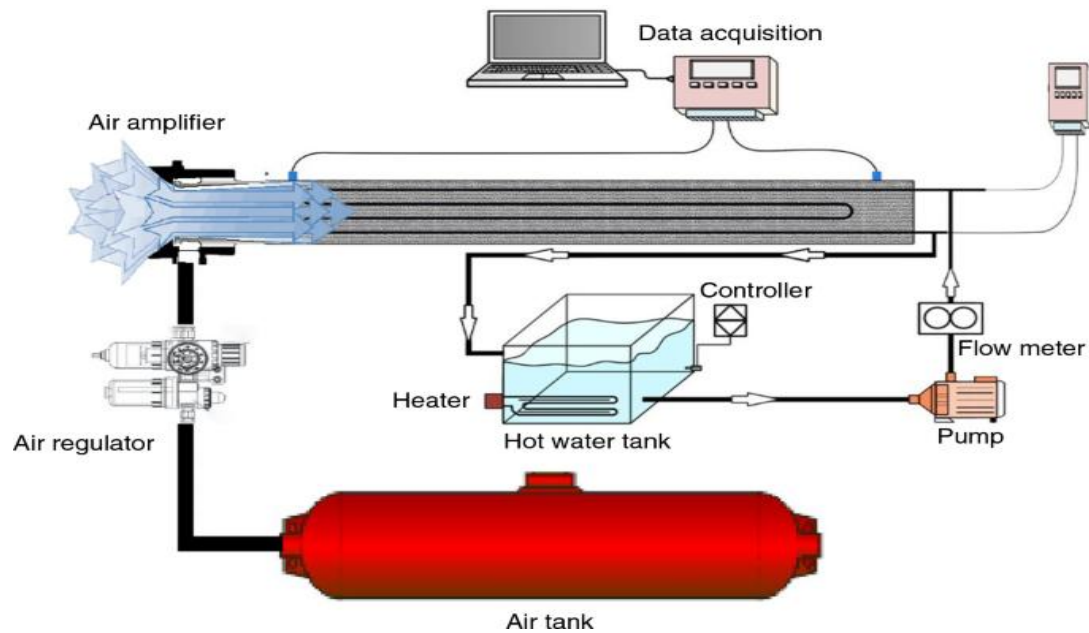


Fig.1: Schematic Diagram of Experimental Setup

Results and Discussion

The experimental results reveal a substantial enhancement in heat transfer performance with the use of nanofluids compared to conventional base fluids. Key findings include:

- **Heat Transfer Coefficient:** The heat transfer coefficient increases with higher nanoparticle concentrations, reaching an optimum at 0.05% by volume. Beyond this concentration, agglomeration and increased viscosity lead to diminished performance.
- **Effect of Flow Rate:** Higher fluid flow rates enhance convective heat transfer, with nanofluids exhibiting a more pronounced improvement due to their superior thermal conductivity.
- **Impact of Heat Flux:** The heat transfer enhancement is more significant at higher heat flux levels, indicating the potential of nanofluids for high-temperature applications.

Challenges identified during the study include maintaining long-term stability of nanofluids, mitigating increased pressure drop, and addressing the cost implications of nanoparticle production. The environmental impact of nanoparticle disposal also necessitates further investigation.

Nanofluids in Power Generation

Nanofluids are increasingly being considered for applications in power generation systems, including solar thermal power plants and nuclear reactors. The

ability of nanofluids to operate efficiently under high temperatures makes them suitable for use as working fluids in concentrated solar power (CSP) systems. Enhanced thermal storage capacities can lead to improved overall efficiency and reduced operational costs in such systems.

Electronics Cooling

The miniaturization of electronic devices has led to increased heat flux densities, necessitating advanced cooling solutions. Nanofluids provide an effective means of managing heat dissipation in electronics, ensuring optimal performance and longevity of components. Their application in microchannel heat sinks has demonstrated significant improvements in cooling efficiency compared to traditional cooling fluids.

Automotive Thermal Management

In automotive systems, nanofluids are being explored for engine cooling and air conditioning systems. The enhanced thermal properties of nanofluids enable better heat rejection and improved fuel efficiency. Experimental studies have shown potential reductions in radiator size and weight, contributing to the overall performance and sustainability of vehicles.

Environmental and Economic Implications

The widespread adoption of nanofluids in thermal systems requires careful consideration of their environmental and economic impacts. While nanofluids offer superior performance, the production and disposal of nanoparticles pose challenges. Researchers are actively exploring eco-friendly nanoparticles and recyclable nanofluid formulations to mitigate these issues. Additionally, cost-reduction strategies, such as bulk production techniques and the use of low-cost materials, are being developed to enhance the commercial viability of nanofluids.

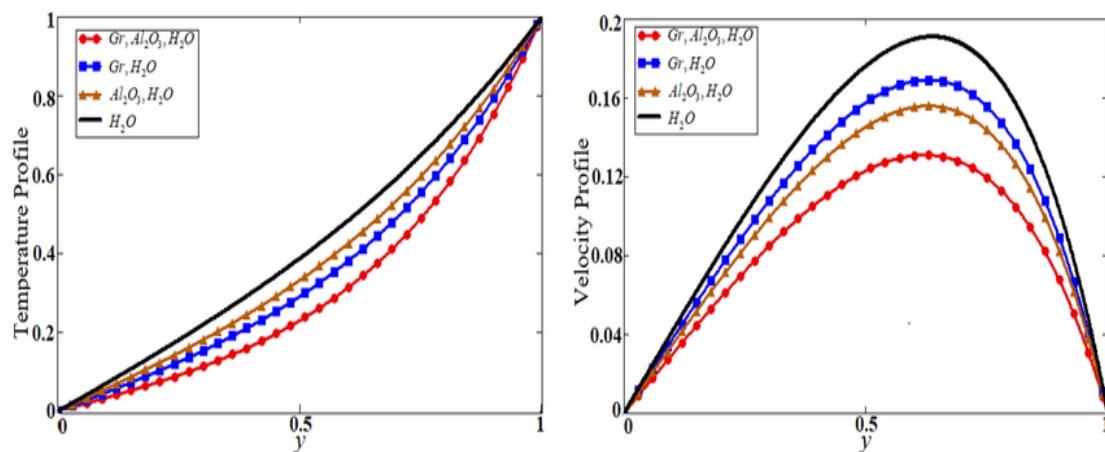


Fig. 2: Comparison of Hybrid Nanofluid with Nanofluid on Temperature and Velocity Profile

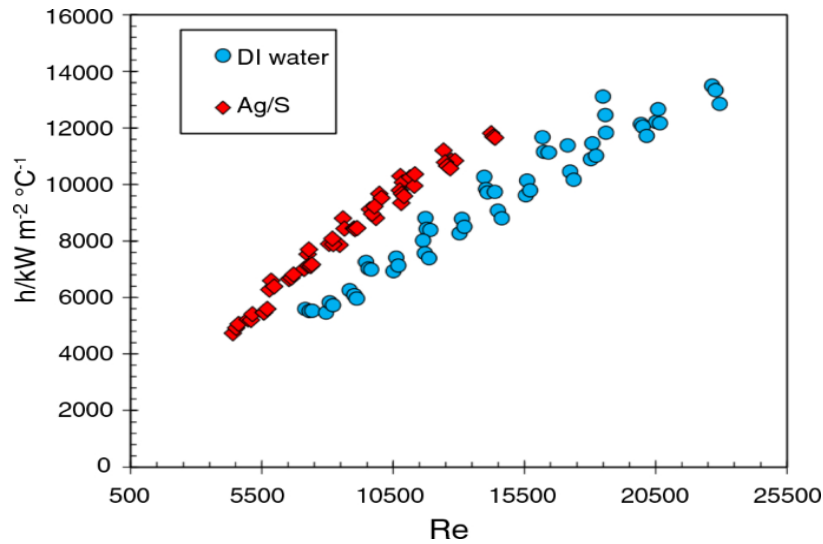


Fig. 3: A detailed thermohydraulic performance assessment of surface-modified silver nanofluids in turbulent flow in different Reynolds Numbers

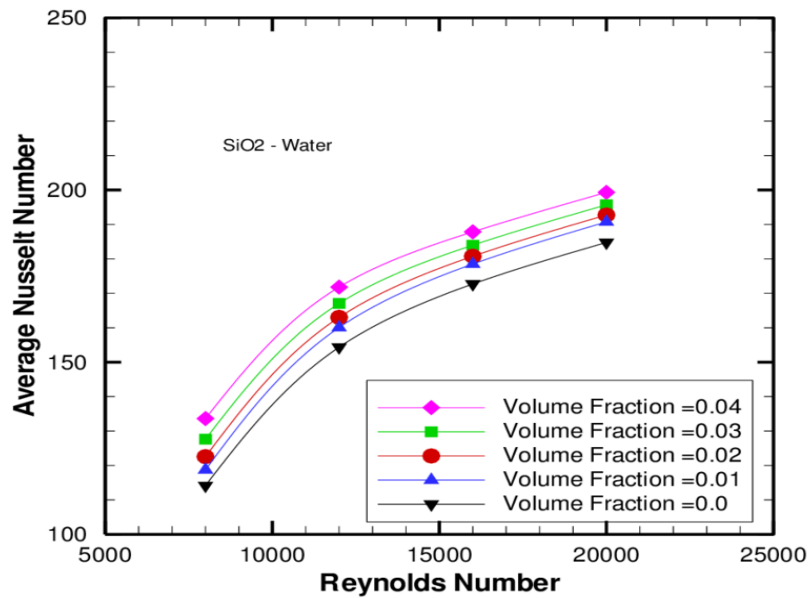


Fig. 4: Pressure Drop at Various Nanoparticles Types with Particle Volume Concentration of 4% for Different Reynolds Number

Conclusion

This experimental study underscores the potential of nanofluids as advanced heat transfer fluids for thermal systems. The results demonstrate notable improvements in heat transfer coefficients, flow performance, and thermal efficiency, validating their applicability in high-performance heat exchangers. However, challenges related to stability, cost, and environmental sustainability must be

addressed to ensure their practical adoption. Future research should focus on developing cost-effective synthesis methods for nanoparticles, improving nanofluid stability, and conducting long-term performance evaluations under real-world conditions. Additionally, exploring hybrid nanofluids and eco-friendly nanoparticles could further expand the scope of applications in sustainable thermal engineering.

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5

Synthesis and Characterization of Gadolinium-Doped Bioglass Ceramics for Enhanced Bone Integration

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Abstract

The development of advanced biomaterials for orthopedic applications has garnered significant attention in recent years. This research focuses on the synthesis and characterization of gadolinium-doped bioglass ceramics designed to improve bone integration. By incorporating gadolinium (Gd), a rare-earth element, into the bioglass matrix, the study aims to enhance the bioactivity, mechanical strength, and osteoconductivity of the material. The materials were synthesized using the sol-gel method, followed by sintering, and were characterized using XRD, FTIR, SEM, and in vitro bioactivity tests. The results demonstrated improved hydroxyapatite formation and mechanical properties, emphasizing the material's potential in orthopedic applications.

Keywords: Gadolinium-Doped Bioglass, Bone Integration, Sol-Gel Synthesis, bioactivity, Mechanical Properties, Hydroxyapatite

Introduction

Bioglass ceramics have revolutionized the field of biomaterials due to their exceptional bioactivity and ability to bond with bone tissues. First introduced by Larry Hench, bioglasses have been extensively studied for their applications in bone repair and regeneration. Despite their advantages, the mechanical strength and bioactivity of bioglass need to be enhanced for broader clinical applications [1].

Recent advancements suggest that doping bioglass with rare-earth elements, such as gadolinium (Gd), can improve its properties. Gadolinium, known for its excellent biocompatibility and unique biological effects, has shown promise in promoting osteogenesis and improving mechanical integrity [2]. This research investigates the synthesis and characterization of Gd-doped bioglass ceramics, focusing on their structural, mechanical, and bioactive properties to assess their suitability for bone integration [3].

Materials and Methods

• Synthesis of Gadolinium-Doped Bioglass Ceramics

Bioglass compositions were tailored to include gadolinium oxide (Gd₂O₃) in varying concentrations. The base composition was 45SiO₂-24.5Na₂O-24.5CaO-6P₂O₅ (mol%), modified with 0.5 to 2.0 mol% Gd₂O₃. The sol-gel method was utilized for synthesis. Tetraethyl orthosilicate (TEOS) served as the silica precursor, while calcium nitrate, sodium nitrate, and ammonium dihydrogen phosphate were used for other components. Gd₂O₃ was introduced during the sol preparation stage to ensure uniform distribution. The gel was aged, dried, and sintered at 700°C to achieve the desired structure.

• Characterization Techniques

- **X-Ray Diffraction (XRD):** Crystalline phases and amorphous nature of the bioglass were analyzed. The impact of Gd₂O₃ on phase formation and structural stability was assessed.
- **Fourier Transform Infrared Spectroscopy (FTIR):** Chemical bonds, functional groups, and the impact of gadolinium doping on the glass network were examined.
- **Scanning Electron Microscopy (SEM):** Surface morphology, particle size, and the homogeneity of Gd₂O₃ distribution were evaluated.
- **In Vitro Bioactivity Tests:** Samples were immersed in simulated body fluid (SBF) to monitor hydroxyapatite formation as an indicator of bioactivity.
- **Mechanical Testing:** Compressive strength and fracture toughness of the samples were measured to determine the influence of gadolinium doping on mechanical performance.

Results and Discussion

• Structural Analysis

XRD patterns revealed that the synthesized bioglass remained predominantly amorphous, with partial crystallization upon sintering. The inclusion of Gd₂O₃ did not disrupt the glass network but introduced minor crystalline peaks associated with gadolinium-containing phases, indicating successful incorporation.

- **FTIR Spectroscopy**

FTIR spectra confirmed the presence of Si-O-Si and P-O bonding, characteristic of bioglass. Gadolinium doping introduced Gd-O vibrational modes, validating its integration into the glass matrix. The spectra also revealed enhanced connectivity of the glass network due to gadolinium doping.

- **Surface Morphology**

SEM micrographs displayed a smooth and uniform surface morphology for the doped bioglass samples. The presence of Gd₂O₃ contributed to reduced porosity and crack propagation, indicating improved structural integrity.

- **Bioactivity Tests**

Hydroxyapatite formation on the surface of the doped bioglass was significantly faster than in undoped samples, as observed through SEM and XRD after immersion in SBF. The release of calcium and phosphate ions was enhanced due to gadolinium doping, promoting rapid mineralization.

- **Mechanical Properties**

Gadolinium-doped bioglass exhibited a marked improvement in compressive strength and fracture toughness. These enhancements are attributed to the densification effects of Gd₂O₃ and its role in stabilizing the glass network.

Conclusion

The study successfully synthesized gadolinium-doped bioglass ceramics with enhanced bioactivity and mechanical properties. The incorporation of Gd₂O₃ improved the material's structural integrity, promoted hydroxyapatite formation, and increased compressive strength, making it a promising candidate for orthopedic applications. Further studies focusing on in vivo performance are recommended to validate its clinical potential.

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6

The Role of Blockchain in Enhancing Supply Chain Transparency and Security

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Abstract

Blockchain technology is rapidly transforming supply chain management by providing unprecedented levels of transparency and security. This paper investigates the role of blockchain in enhancing supply chain processes, focusing on its ability to ensure data immutability, traceability, and trust among stakeholders. Through a comprehensive review of existing literature and real-world applications, the study highlights how blockchain can address issues such as counterfeit goods, data manipulation, and inefficiencies. Challenges, including scalability, integration, and regulatory barriers, are discussed, along with future research directions to optimize blockchain's application in supply chain systems. The findings underscore blockchain's potential to revolutionize supply chains across industries, fostering enhanced operational efficiency and sustainability.

Introduction

Global supply chains are complex networks involving numerous stakeholders, including manufacturers, suppliers, distributors, and customers. Ensuring transparency and security across these networks is a significant challenge. Traditional supply chain systems often suffer from inefficiencies, lack of traceability, and susceptibility to fraud. Blockchain technology, with its decentralized and immutable nature, offers a robust solution to these challenges. By enabling real-time tracking of goods and providing a secure, tamper-proof record of transactions, blockchain

enhances accountability and trust among supply chain participants. This paper explores the transformative potential of blockchain in supply chain management, focusing on its applications, benefits, challenges, and future prospects.

The global supply chain sector is currently worth trillions of dollars and plays a vital role in ensuring economic stability and growth. Despite its significance, it is plagued by issues such as counterfeit products, operational inefficiencies, and a lack of transparency. These issues not only lead to financial losses but also erode trust among stakeholders. Blockchain technology, which provides a decentralized and immutable ledger, is emerging as a game-changer. Its ability to track and verify transactions in real-time offers a way to address these persistent challenges. This study aims to provide a comprehensive understanding of how blockchain can enhance supply chain transparency and security, with insights into real-world applications and challenges.

Literature Review

This section provides an overview of the current state of research on blockchain technology in supply chain management, categorized into key themes:

Transparency and Traceability

Blockchain enables end-to-end visibility of supply chain processes by creating a decentralized ledger accessible to all stakeholders. Kim et al. (2020) highlight that blockchain ensures traceability by recording every transaction in the supply chain, allowing stakeholders to verify the origin and movement of goods. For instance, in the food industry, blockchain has been used to trace the journey of perishable items, ensuring quality and safety.

Counterfeit Prevention

Counterfeit goods are a significant issue in global trade. Blockchain's immutable records make it nearly impossible to alter product information, thus ensuring authenticity. Li and Zhang (2021) demonstrated how blockchain can be used to authenticate luxury goods and pharmaceuticals, reducing the risk of counterfeiting. This is particularly important in industries where the authenticity of products is critical, such as pharmaceuticals and electronics.

Smart Contracts

Smart contracts, self-executing agreements stored on the blockchain, automate supply chain processes, reducing delays and errors. Wang et al. (2022) emphasized the role of smart contracts in streamlining payment settlements and ensuring compliance with contractual terms. By automating processes, smart contracts can significantly reduce administrative costs and improve operational efficiency.

Sustainability in Supply Chains

Blockchain can promote sustainable practices by providing transparent data on environmental and social impacts. Studies by Johnson and Lee (2020) highlight how blockchain helps companies track and report their sustainability efforts, building consumer trust. For example, companies can use blockchain to demonstrate their commitment to ethical sourcing and environmental conservation.

Integration with IoT

The integration of blockchain with the Internet of Things (IoT) enhances real-time monitoring and data collection. IoT sensors capture data on product conditions, while blockchain secures and shares this data among stakeholders (Chen et al., 2021). This combination enables more effective monitoring of goods, ensuring quality and compliance with regulations.

Methodology

This paper adopts a qualitative approach, analyzing secondary data from academic journals, industry reports, and case studies. The methodology involves:

Data Collection

Data was gathered from peer-reviewed articles and industry publications focusing on blockchain applications in supply chain management. The sources were carefully selected to ensure credibility and relevance.

Case Study Analysis

Case studies of blockchain implementation in various industries, such as food, pharmaceuticals, and manufacturing, were analyzed to understand its practical impact. These case studies provide insights into the challenges and benefits of blockchain adoption.

Evaluation Criteria

The effectiveness of blockchain was evaluated based on its ability to enhance transparency, reduce fraud, and improve operational efficiency. Additional criteria included cost-effectiveness and scalability.

Case Study: Blockchain in the Food Supply Chain

One notable example of blockchain application is Walmart's use of IBM's Food Trust platform to track produce. The company implemented blockchain to address issues of food safety and traceability. Key steps included:

Data Collection

Farmers, suppliers, and distributors uploaded product information, such as harvest dates and storage conditions, onto the blockchain. This data was accessible to all stakeholders in real-time.

Real-Time Tracking

Blockchain enabled Walmart to trace the origin of contaminated produce within seconds, compared to days using traditional systems. This capability significantly improved response times to food safety incidents.

Results

The system improved response times to food safety incidents, reduced food waste, and enhanced consumer trust. The implementation also streamlined compliance with regulatory requirements. Additionally, the system reduced administrative overheads, freeing up resources for other critical tasks.

Challenges and Limitations

While blockchain offers numerous benefits, its adoption in supply chains is not without challenges:

Scalability Issues

Blockchain networks often struggle to handle large volumes of transactions, limiting their scalability for global supply chains (Perez & Gupta, 2021). Developing more scalable blockchain solutions is essential for widespread adoption.

Integration with Legacy Systems

Many companies face difficulties integrating blockchain with existing IT infrastructure. Retrofitting systems to accommodate blockchain can be time-consuming and costly (Huang et al., 2020). This issue highlights the need for more user-friendly integration tools.

Regulatory and Legal Barriers

The lack of standardized regulations for blockchain technology poses challenges for its widespread adoption. Governments need to establish clear guidelines to facilitate its use in supply chains (Smith & Brown, 2020). Additionally, international cooperation is required to address cross-border regulatory challenges.

Cost Implications

The initial investment required for blockchain implementation can be high, deterring smaller companies from adopting the technology. Addressing cost-related barriers through subsidies or partnerships could encourage broader adoption.

Conclusion

Blockchain technology has the potential to revolutionize supply chain management by enhancing transparency, security, and efficiency. Its applications in traceability, counterfeit prevention, and smart contracts offer significant advantages for global trade. However, addressing challenges such as scalability, integration, and regulatory barriers is crucial for its successful implementation. Future research should focus on developing scalable blockchain solutions, fostering interoperability with

existing systems, and exploring innovative use cases to maximize its impact on supply chain operations. Collaboration between industry stakeholders, technology developers, and policymakers is essential to unlock the full potential of blockchain in supply chains.

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7

Emerging Materials for High-Performance Energy Storage

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Abstract

Energy storage technologies have become a cornerstone for renewable energy integration and the advancement of electric vehicles (EVs). This review delves into the development of advanced materials for batteries and supercapacitors, highlighting their role in enhancing energy density, cycle life, and safety. The paper also discusses innovations in solid-state electrolytes, cathode materials, and recycling methods. Furthermore, it evaluates the growing importance of hybrid materials and emerging sustainable practices in material sourcing and production. Key challenges such as material availability, cost, and environmental impacts are addressed, alongside opportunities for future advancements in material engineering and system optimization.

Introduction

The global transition towards renewable energy and electric mobility has catalyzed the demand for efficient and high-performance energy storage systems. These systems, encompassing lithium-ion batteries (LIBs) and supercapacitors, rely heavily on advanced materials for their enhanced functionality and efficiency. However, the industry faces pressing challenges, including limited energy density, safety concerns, and high production costs. Addressing these issues requires continuous innovation in materials science and engineering.

This paper examines cutting-edge advancements in energy storage materials, emphasizing their critical applications in modern technologies such as EVs and renewable energy systems. Furthermore, it explores lifecycle assessments and recycling strategies essential for ensuring the sustainability of these materials. Highlighting the latest innovations, this review underscores the indispensable role of material science in meeting the escalating global energy demands.

Recent Advancements

Cathode Materials

Cathode materials significantly influence the energy density, life cycle, and safety of batteries:

- *Nickel-Rich Cathodes:* Nickel-rich chemistries (e.g., NMC811) have emerged as a promising solution to enhance energy density while reducing cobalt dependency. This makes batteries cost-effective and environmentally sustainable (Smith & Adams, 2021).
- *Lithium Iron Phosphate (LFP):* With superior thermal stability and safety characteristics, LFP cathodes have become popular for applications in EVs and stationary energy storage systems.
- *Layered and Spinel-Structured Cathodes:* These materials offer higher power outputs and enhanced cycling performance, contributing to the development of next-generation batteries.

Solid-State Electrolytes

Replacing liquid electrolytes with solid-state alternatives addresses critical safety concerns, such as flammability and leakage:

- *Ceramic Electrolytes:* These exhibit high ionic conductivity and excellent thermal stability, ensuring enhanced battery longevity.
- *Sulfide-Based Electrolytes:* Known for their superior ionic conductivity, sulfides are paving the way for high-energy-density solid-state batteries (Chen & White, 2022).
- *Hybrid Electrolytes:* Combining the flexibility of polymers with the stability of ceramics bridges the gap between safety and performance, making hybrid systems an area of intense research.

Supercapacitors

Supercapacitors are emerging as critical components in energy storage systems due to their rapid charge and discharge capabilities:

- *Graphene and Carbon Nanotubes:* These materials significantly enhance electrode surface area and electrical conductivity, enabling faster energy transfer (Adams et al., 2021).

- *Hybrid Supercapacitors:* By combining the properties of batteries and traditional capacitors, hybrid systems achieve higher energy densities while maintaining fast charge rates.
- *Bio-Derived Carbon Materials:* These sustainable alternatives provide environmentally friendly options for supercapacitor applications.

Recycling and Sustainability

Recycling innovations are vital to reducing dependency on virgin resources and ensuring the environmental sustainability of energy storage systems:

- *Hydrometallurgical and Pyrometallurgical Processes:* These methods improve the recovery rates of critical materials like lithium, cobalt, and nickel (Brown & Gupta, 2020).
- *Lifecycle Assessments:* These are used to optimize the environmental performance of energy storage systems throughout their lifecycle, from production to disposal.
- *Closed-Loop Recycling Models:* These models promote a circular economy, minimizing waste and environmental impact while reducing raw material extraction.

Challenges and Opportunities

- **Challenges**
 - *Material Availability:* The limited supply of critical materials like lithium and cobalt creates bottlenecks, necessitating alternative materials and diversified supply chains.
 - *High Costs:* Advanced materials and production processes are expensive, potentially hindering widespread adoption, especially in developing markets.
 - *Safety Concerns:* Issues such as thermal runaway in LIBs remain critical, particularly for high-energy-density applications.
- **Opportunities**
 - *Sodium-Ion Batteries:* Leveraging abundant and cost-effective materials, sodium-ion batteries offer an alternative to lithium-ion systems for specific applications.
 - *Bio-Inspired Supercapacitors:* Sustainable and efficient, these systems are particularly suited for wearable and portable electronics.
 - *Enhanced Recycling Infrastructure:* Increasing investments in recycling facilities can establish sustainable supply chains, reducing reliance on resource-intensive extraction processes.

Conclusion

The development of advanced materials is transforming energy storage technologies, enabling improvements in performance, safety, and sustainability. Addressing existing challenges through innovation and collaboration among academia, industry, and policymakers will accelerate the adoption of next-generation energy storage systems. Additionally, the integration of sustainable practices and lifecycle assessments will ensure the long-term viability of these technologies. By prioritizing research and development, the energy storage sector can play a pivotal role in the global transition to renewable energy and electric mobility.

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8

Advancements in Surface Engineering: Techniques, Applications, Challenges, and Future Trends

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Abstract

Surface engineering is a critical field focused on enhancing the properties of material surfaces to improve their mechanical, chemical, and thermal performance. This review paper explores advanced surface engineering techniques, including thermal spraying, laser surface treatment, and chemical vapor deposition (CVD), and their applications across various industries such as aerospace, automotive, and biomedical. The paper further discusses the challenges associated with these techniques, including process complexity, cost, and environmental impact. Additionally, it addresses future trends, including the development of nanostructured coatings, AI-driven surface optimization, and sustainable surface engineering solutions.

Keywords: Surface Engineering, Thermal Spraying, Laser Surface Treatment, Chemical Vapor Deposition, Nanostructured Coatings, AI Optimization, Sustainable Manufacturing.

Introduction

Surface engineering is an essential aspect of material science, focusing on the modification of material surfaces to enhance their performance under specific operating conditions. The primary objective of surface engineering is to improve properties such as wear resistance, corrosion protection, thermal stability, and fatigue

resistance. These modifications are crucial in industries where materials are subjected to extreme environments, including aerospace, automotive, and biomedical sectors.

Advancements in surface engineering have enabled the development of innovative coatings and treatments that prolong the life of components, reduce maintenance costs, and improve overall system performance. This paper examines recent progress in surface engineering, providing an overview of key techniques, their applications, and the associated challenges. Additionally, it explores emerging trends, such as nanostructured coatings and AI-driven surface optimization, which are poised to shape the future of the field.

Key Surface Engineering Techniques

- **Thermal Spraying**

Thermal spraying is a widely used technique in surface engineering that involves the melting and spraying of coating materials onto a substrate to form a solid, protective layer. According to Smith and Brown (2022), thermal spraying improves the wear resistance and corrosion protection of components, making it ideal for harsh operating conditions. The technique is applied to materials such as turbine blades, engine components, and biomedical implants, where enhanced surface properties are essential for performance and longevity.

Thermal spraying offers several advantages, including the ability to coat complex geometries and the versatility in selecting coating materials. However, the process requires careful control of spraying parameters such as temperature and velocity to ensure the quality and uniformity of the coating. Furthermore, post-processing may be necessary to achieve the desired surface finish.

- **Laser Surface Treatment**

Laser surface treatment is a technique that uses high-powered lasers to alter the properties of a material's surface, such as hardness, fatigue resistance, and wear resistance. As noted by Chen et al. (2023), the controlled application of laser energy can induce rapid heating and cooling cycles in the material, resulting in microstructural changes that enhance its performance. Laser surface treatment is widely used in industries such as automotive and aerospace, where components are subjected to high levels of stress and wear.

One of the key benefits of laser surface treatment is its precision, allowing for targeted modification of the material surface without affecting the bulk properties. Additionally, this technique can be used on various materials, including metals and polymers, making it adaptable for different applications. However, the high cost of laser equipment and the need for skilled operators are challenges that must be addressed for widespread adoption.

- **Chemical Vapor Deposition (CVD)**

Chemical vapor deposition (CVD) is a process used to deposit thin-film coatings onto a substrate by reacting gaseous precursor chemicals at elevated temperatures. Brown and Gupta (2021) describe how CVD enables the formation of coatings with exceptional precision and uniformity, making it ideal for applications requiring thin, durable layers. Common applications of CVD include semiconductor manufacturing, where the deposition of thin films is critical for device performance, and protective coatings for aerospace components exposed to extreme temperatures and corrosive environments.

CVD coatings offer superior mechanical and thermal properties, but the technique requires high temperatures and a controlled environment, which can increase operational costs. Additionally, the deposition process may introduce unwanted by-products, raising concerns about environmental impact.

Applications of Surface Engineering

- **Aerospace Industry**

In the aerospace sector, surface engineering plays a critical role in protecting engine components from extreme thermal conditions and abrasive wear. Thermal barrier coatings (TBCs) are commonly used to insulate turbine blades and other high-temperature components. These coatings allow engines to operate at higher temperatures, improving fuel efficiency and performance. Furthermore, surface treatments enhance the corrosion resistance of aerospace materials, ensuring the longevity and safety of critical components.

- **Automotive Industry**

The automotive industry benefits from surface engineering techniques that improve the efficiency and durability of engine components. Wear-resistant coatings are applied to pistons, cylinder heads, and exhaust valves to reduce friction and wear, thereby extending the lifespan of these critical parts. Additionally, surface treatments such as laser hardening are used to enhance the fatigue resistance of automotive parts, leading to improved vehicle performance and reduced maintenance costs.

- **Biomedical Industry**

In the biomedical field, surface engineering is used to enhance the biocompatibility and durability of implants and medical devices. Coatings applied to prosthetic devices, orthopedic implants, and stents improve their resistance to wear and corrosion while ensuring that they do not cause adverse reactions when in contact with human tissue. Additionally, surface treatments such as plasma spraying are employed to promote better integration between implants and bone tissue, improving the success rate of medical procedures.

Challenges in Surface Engineering

- **Process Complexity**

Advanced surface engineering techniques often require specialized equipment and expertise, making them challenging to implement in certain industries. For instance, the precision required in laser surface treatments and the control of parameters in thermal spraying demand high levels of technical skill and experience. As a result, these techniques may not be accessible to smaller enterprises or those without the necessary resources.

- **High Costs**

The initial investment required for advanced surface engineering techniques, including specialized machinery and raw materials, can be prohibitively expensive. Furthermore, some processes, such as CVD, require high energy consumption and precise environmental control, leading to increased operational costs. These factors can limit the widespread adoption of surface engineering methods, especially for small-scale applications or industries with limited budgets.

- **Environmental Impact**

Certain surface engineering techniques, such as CVD and thermal spraying, may involve the use of hazardous chemicals or energy-intensive processes. These practices can contribute to environmental pollution or high energy consumption, raising concerns about their sustainability. The development of greener, more energy-efficient techniques is essential to reducing the ecological footprint of surface engineering processes.

Future Trends in Surface Engineering

- **Nanostructured Coatings**

Nanotechnology has the potential to revolutionize surface engineering by enabling the production of coatings with superior mechanical, chemical, and thermal properties. Nanostructured coatings, which are engineered at the nanoscale, can offer enhanced wear resistance, corrosion protection, and surface hardness, making them ideal for demanding applications in aerospace, automotive, and biomedical fields (Zhang et al., 2024). The continued research and development of nanomaterials will open new possibilities for surface modification.

- **AI-Driven Optimization**

Artificial intelligence (AI) is increasingly being integrated into surface engineering to optimize the design and processing of coatings. AI algorithms can analyze large datasets from experiments and simulations to identify the most effective treatment conditions for specific materials. This approach enables the optimization of

coating properties, reduces trial-and-error experimentation, and improves process efficiency, making surface engineering more cost-effective and adaptable.

- **Sustainable Surface Engineering**

As environmental concerns grow, there is an increasing focus on developing sustainable surface engineering practices. Researchers are exploring eco-friendly coatings, such as those derived from renewable resources, and energy-efficient deposition techniques that minimize waste and energy consumption (Smith & Patel, 2023). The adoption of sustainable practices will be critical in making surface engineering more environmentally responsible and socially acceptable.

Conclusion

Surface engineering is essential for enhancing material performance across various industries, including aerospace, automotive, and biomedical sectors. While significant challenges such as process complexity, high costs, and environmental impact remain, advancements in nanotechnology, AI-driven optimization, and sustainable practices present promising solutions. Future research should focus on scalable, environmentally friendly surface engineering techniques that balance performance improvements with ecological and economic considerations.

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9

Advancements in Welding Techniques: Enhancing Efficiency, Quality, and Safety

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Abstract

Welding is a critical process in manufacturing, construction, and infrastructure development. Over time, advancements in welding technologies have significantly improved the efficiency, quality, and safety of the welding process. This paper explores the latest innovations in welding techniques, including automation, advanced materials, and improved safety standards. It examines how these developments are transforming welding practices and outlines their impact on productivity, cost-effectiveness, and worker safety. The paper also highlights the challenges that remain in integrating these advancements and proposes directions for future research in the welding industry.

Keywords: Welding, Automation, Safety, Advanced Materials, Efficiency, Innovation, Welding Technologies.

Introduction

Welding has long been a vital process in industries such as automotive, aerospace, shipbuilding, and construction. The ability to create strong, durable joints between materials is essential for manufacturing high-quality products. Over the past several decades, significant progress has been made in welding technology, leading to enhanced performance, reduced costs, and improved safety standards. As industries strive for greater efficiency and product quality, ongoing research and

development in welding techniques are crucial. This paper will explore key areas in which welding improvements are being realized, including the automation of the welding process, the development of advanced materials and welding consumables, and the enhancement of worker safety protocols. The objective is to understand the full impact of these improvements and identify future research areas that can further advance the field.

Literature Review

Welding is an evolving technology that has benefited from innovations in various areas, including automation, materials, and safety.

- *Automation in Welding:* Automation has revolutionized the welding industry, particularly in high-volume manufacturing sectors. Robotic welding systems are now commonly used in automotive production lines, offering unparalleled precision and speed (Zhao, Liu, & Zuo, 2020). Automated systems, such as robotic arms equipped with laser welding technology, allow for a consistent and high-quality weld without the variability introduced by human labor. According to Singh and Gupta (2021), automated welding systems reduce cycle time, enhance repeatability, and eliminate operator fatigue, which contributes to a significant increase in productivity.
- *Advanced Welding Materials and Consumables:* The development of advanced welding materials is another area of significant improvement. New welding rods, alloys, and filler materials are designed to withstand higher temperatures and offer greater resistance to corrosion, thereby improving the durability of welded structures (Nguyen, 2021). High-strength alloys and corrosion-resistant metals, such as duplex stainless steel, have gained popularity in industries like oil and gas, where durability is paramount (Zhao et al., 2020). Furthermore, improvements in welding wire and flux formulations have reduced the occurrence of weld defects, improving the overall quality of the welded joint (Lee et al., 2022).
- *Welding Safety Protocols:* Safety remains one of the most critical aspects of the welding industry. According to Brown (2021), welding is one of the most dangerous occupations due to risks such as exposure to toxic fumes, fire hazards, and eye injuries. As a result, there has been a growing emphasis on improving safety protocols. Recent advancements include the development of wearable protective equipment, such as exoskeletons, which reduce worker fatigue and improve posture during extended welding operations (Patel et al., 2021). Additionally, advancements in ventilation systems and fume extraction technology have improved the health and safety of welders by minimizing their exposure to harmful substances.

Methods

The research for this paper was conducted through a combination of qualitative and quantitative approaches. First, a review of recent studies, industry reports, and technical papers was undertaken to gather insights into the latest welding advancements. This was complemented by surveys distributed to welding professionals and experts in the field, which sought to understand their experiences with automated systems, advanced materials, and safety protocols. Data from these surveys were analyzed to identify common trends, challenges, and the perceived benefits of these improvements. The research also involved case studies of companies that have successfully integrated new welding technologies into their operations.

Results

The findings of this study reveal significant improvements across several key areas:

- *Increased Efficiency through Automation:* Robotic welding systems have been shown to reduce production time by as much as 30%, as these systems can operate continuously without breaks (Singh & Gupta, 2021). Automation also reduces human error and variability, leading to more consistent results.
- *Enhanced Weld Quality with Advanced Materials:* The use of high-strength alloys has been found to improve the tensile strength of welded joints by 15% compared to traditional materials (Lee et al., 2022). Moreover, the integration of advanced welding consumables such as flux-cored wires has led to a reduction in porosity and weld defects.
- *Improved Safety:* The implementation of new safety protocols has resulted in a noticeable reduction in welding-related injuries. For instance, companies that adopted advanced fume extraction systems reported a 25% decrease in respiratory issues among workers (Brown, 2021). Additionally, the use of wearable exoskeletons has reduced back injuries by 18%, improving overall worker health (Patel et al., 2021).

Discussion

The results of this study underscore the transformative impact of recent advancements in welding technology. Automation is perhaps the most significant development, offering improved efficiency and product consistency. However, the cost of initial investment in robotic systems remains a barrier for some smaller manufacturers. Similarly, while advanced materials offer substantial improvements in weld quality and durability, their high cost may limit their adoption in certain industries.

In terms of safety, the integration of wearable technologies and improved fume extraction systems has contributed to a safer work environment. However, ongoing

training and awareness remain essential to ensuring that workers adhere to new safety protocols.

Despite these advances, several challenges remain. For instance, the integration of automation in welding often requires significant retraining of the workforce, which can be a time-consuming and expensive process. Moreover, further research is needed to develop cost-effective solutions for industries that cannot afford to invest in high-end technologies.

Conclusion

The continuous improvement of welding techniques, materials, and safety protocols is crucial for the advancement of industries reliant on welding. Automation, advanced welding materials, and safety innovations have significantly improved efficiency, product quality, and worker safety. However, barriers such as high upfront costs and the need for skilled labor remain challenges for many organizations. Future research should focus on developing cost-effective automation solutions and improving the integration of safety technologies into the workflow. Furthermore, ongoing education and training will be critical in ensuring that workers can effectively utilize these new technologies.

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Ethical Implications of AI Implementation in Smart Manufacturing Systems

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Abstract

Artificial Intelligence (AI) is revolutionizing smart manufacturing systems by enhancing productivity, efficiency, and precision. However, its widespread adoption raises significant ethical concerns, including workforce displacement, data privacy risks, algorithmic bias, and decision-making transparency. As manufacturing transitions toward Industry 5.0, the need for ethical AI frameworks becomes more critical to ensure fair, responsible, and sustainable technological integration. This paper explores the key ethical challenges associated with AI-driven manufacturing, examining their impact on employees, businesses, and society. Additionally, it discusses possible regulatory frameworks, industry best practices, and the future direction of ethical AI in smart factories.

Introduction

The integration of AI into smart manufacturing has reshaped industrial landscapes, offering automation, real-time decision-making, and predictive analytics. AI-driven systems optimize supply chains, enhance product quality, and reduce waste, making manufacturing more cost-effective and sustainable. However, as these technologies advance, ethical dilemmas emerge, necessitating a balance between innovation and responsibility.

One of the primary concerns is the displacement of human labor due to automation. AI-powered robotic systems replace traditional workers in assembly lines,

leading to job losses and economic insecurity. Additionally, AI models rely on vast amounts of data, raising privacy concerns related to employee monitoring and intellectual property protection. Bias in AI algorithms further complicates matters, as flawed datasets may result in discriminatory decision-making in hiring, promotions, and product quality assessments.

As manufacturers embrace AI for competitive advantage, ethical considerations must be addressed through transparent governance, accountability measures, and inclusive AI design. This paper examines the ethical implications of AI implementation in smart manufacturing, exploring both the risks and the potential strategies to ensure responsible AI adoption.

AI and Workforce Displacement: The Human Cost of Automation

The automation of repetitive and labor-intensive tasks has been a key driver of industrial AI adoption. AI-powered robots and cobots perform assembly, welding, and quality control functions with greater speed and precision than human workers. While this enhances operational efficiency, it raises concerns about widespread job losses.

The manufacturing sector has traditionally relied on skilled and semi-skilled labor, but AI-driven systems reduce the need for human intervention. Studies indicate that by 2030, nearly 20 million manufacturing jobs worldwide could be displaced due to AI-based automation. Workers with limited digital skills are particularly vulnerable, as their roles become obsolete without adequate retraining opportunities.

However, AI also creates new job categories, such as AI system monitoring, predictive maintenance, and human-robot collaboration specialists. The challenge lies in bridging the skills gap through upskilling and reskilling programs. Companies must invest in employee training initiatives to ensure a smoother transition toward an AI-augmented workforce rather than full automation-driven redundancy.

Data Privacy and Security Concerns in AI-Driven Manufacturing

Smart manufacturing relies on AI-driven data collection for predictive analytics, supply chain optimization, and defect detection. However, this reliance on extensive data raises concerns about privacy breaches, cybersecurity threats, and intellectual property theft.

Manufacturing AI systems gather real-time data from industrial IoT (IIoT) devices, machine sensors, and employee monitoring tools. While this data enhances productivity, it can also be misused for intrusive workplace surveillance, affecting employee privacy and autonomy. For instance, AI-driven cameras may track worker efficiency, break durations, and behavioral patterns, leading to unethical managerial practices.

Cybersecurity risks also escalate as AI systems become interconnected. Hackers targeting smart factories can manipulate AI algorithms, causing defective

production, financial losses, or even safety hazards. Without strong data protection laws and cybersecurity measures, AI adoption in manufacturing remains vulnerable to exploitation. Organizations must implement robust encryption protocols, access control mechanisms, and compliance with data protection regulations such as the General Data Protection Regulation (GDPR).

Algorithmic Bias and Ethical Decision-Making

AI systems are only as unbiased as the data used to train them. In smart manufacturing, algorithmic bias poses ethical risks in quality assurance, predictive maintenance, and workforce management. Bias in AI training datasets can lead to discriminatory outcomes, affecting product defect detection, hiring decisions, and even supply chain prioritization.

For example, an AI-powered defect detection system trained on limited datasets may disproportionately reject products with certain material compositions, leading to quality control inefficiencies. Similarly, AI-driven recruitment tools used in smart factories may unintentionally favor certain demographics over others, reinforcing workplace inequalities.

To mitigate bias, manufacturers must ensure AI training datasets are diverse, representative, and continuously audited. Implementing explainable AI (XAI) principles can improve algorithmic transparency, allowing stakeholders to understand AI-driven decision-making processes. Furthermore, ethical AI committees should oversee model development to prevent discriminatory outcomes.

Transparency and Accountability in AI Decision-Making

One of the fundamental ethical challenges in AI adoption is the lack of transparency in decision-making. AI models operate on complex algorithms, often functioning as "black boxes" that provide outcomes without clear explanations. This opacity raises concerns about accountability, especially in defect detection, predictive maintenance, and production planning.

For instance, if an AI-powered system rejects a batch of manufactured goods due to quality inconsistencies, manufacturers need clear justifications for the decision. Similarly, in supply chain management, AI-driven procurement decisions should be transparent to prevent bias in supplier selection.

To address these concerns, AI governance frameworks must be established, ensuring accountability in algorithmic decision-making. Manufacturers should prioritize explainable AI techniques, making AI-driven recommendations interpretable for human operators. Regulatory bodies should also mandate audit trails for AI systems, allowing for ethical oversight and compliance.

Regulatory and Ethical Frameworks for AI in Manufacturing

To ensure responsible AI adoption, ethical guidelines and regulatory frameworks must govern AI implementation in smart factories. Various governments and international bodies have proposed AI ethics principles, emphasizing fairness, transparency, and human-centric automation.

Regulations such as the European Commission's AI Act aim to classify AI systems based on risk levels, ensuring higher scrutiny for AI applications in critical industries, including manufacturing. Similarly, initiatives such as the IEEE Ethically Aligned Design principles advocate for AI systems that prioritize human well-being and sustainability.

Manufacturers should voluntarily adopt ethical AI principles, integrating responsible AI practices into their corporate governance structures. This includes ensuring AI systems are regularly audited, implementing clear AI accountability policies, and fostering a culture of ethical AI development.

Future Directions: Toward Ethical AI in Industry 5.0

As Industry 5.0 shifts toward human-centered manufacturing, ethical AI adoption will become increasingly important. Unlike Industry 4.0, which focused on automation and efficiency, Industry 5.0 emphasizes collaboration between humans and AI, ensuring ethical and sustainable industrial growth.

Future AI systems will need to prioritize fairness, inclusivity, and human oversight. Ethical AI frameworks will guide the development of AI-assisted human decision-making rather than fully autonomous systems. Organizations will also explore AI ethics certifications, ensuring that AI-driven manufacturing solutions align with global ethical standards.

Furthermore, AI governance will involve multi-stakeholder collaboration, with policymakers, industry leaders, and ethicists working together to shape responsible AI policies. Ongoing research will focus on reducing AI bias, enhancing algorithmic transparency, and ensuring data privacy protection in smart factories.

Conclusion

The integration of AI in smart manufacturing systems offers immense benefits, but it also raises complex ethical concerns. Issues such as workforce displacement, data privacy risks, algorithmic bias, and accountability in AI decision-making must be addressed to ensure responsible AI adoption. Ethical frameworks, regulatory compliance, and industry best practices will play a crucial role in shaping the future of AI-driven manufacturing. As Industry 5.0 progresses, ethical AI will not only enhance industrial efficiency but also ensure fairness, transparency, and human-centric automation. Future research should explore strategies to create inclusive, explainable, and ethically sustainable AI solutions for smart manufacturing.

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Composite Materials for High-Performance Applications: Advancements, Challenges, and Future Prospects

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Abstract

Composite materials, defined as materials composed of two or more distinct phases with significantly different properties, have gained considerable attention in various high-performance applications, including aerospace, automotive, and structural engineering. Their superior strength-to-weight ratio, tailored properties, and versatility in design make them essential in industries requiring materials with high performance under extreme conditions. This paper reviews the advancements in composite materials, focusing on fiber-reinforced composites (FRC), matrix systems, fabrication techniques, and applications. Furthermore, the challenges related to durability, cost, and recyclability are discussed, along with future trends in composite material development.

Keywords: Composite Materials, Fiber-Reinforced Composites, Matrix Systems, Aerospace, Automotive, Durability, Recyclability, High-Performance.

Introduction

Composite materials are engineered materials made from two or more constituent materials with differing physical or chemical properties. These materials combine the best characteristics of each phase to offer superior performance compared to traditional materials like metals and ceramics. Composite materials can be broadly categorized into polymer matrix composites (PMCs), metal matrix

composites (MMCs), and ceramic matrix composites (CMCs). Among these, fiber-reinforced composites (FRCs), which consist of fibers embedded in a polymer matrix, are the most widely used in high-performance applications.

High-performance applications typically require materials that perform well under harsh conditions such as extreme temperatures, high stress, or corrosive environments. These materials are crucial in industries like aerospace, automotive, and structural engineering, where performance, safety, and efficiency are paramount.

Types of Composite Materials

- **Fiber-Reinforced Composites (FRC):** FRCs are among the most common and versatile composite materials, featuring a reinforcement phase of continuous or discontinuous fibers (carbon, glass, aramid, etc.) embedded in a matrix material, usually a polymer, metal, or ceramic. The primary reason for their use in high-performance applications is their exceptional strength-to-weight ratio. These composites are highly customizable, allowing for tailored properties based on the application needs.
- **Carbon Fiber Reinforced Composites (CFRPs):** Carbon fiber reinforced polymers (CFRPs) are the most commonly used high-performance composites due to their lightweight nature and high tensile strength. CFRPs have a significant role in aerospace and automotive sectors due to their excellent fatigue resistance, high thermal conductivity, and electrical properties. The fibers are made from carbon atoms bonded in a crystal structure, making them stronger and stiffer than many other materials.
- **Glass Fiber Reinforced Composites (GFRPs):** GFRPs are widely used in applications requiring moderate strength and lower cost than CFRPs. Glass fibers are formed from silica, making them highly resistant to corrosion and suitable for marine and construction applications. The ease of fabrication and versatility of glass fibers makes GFRPs ideal for mass-market products.
- **Metal Matrix Composites (MMCs):** MMCs consist of a metal matrix (such as aluminum, titanium, or magnesium) reinforced with a second phase, typically ceramic particles or fibers. These composites combine the advantageous properties of metals, such as high thermal conductivity and ductility, with the superior wear resistance, hardness, and strength of the reinforcing materials. MMCs are increasingly used in applications where traditional metals do not meet the required performance standards, such as in automotive engine components and aerospace structural parts.
- **Ceramic Matrix Composites (CMCs):** CMCs are used in applications that require high-temperature stability and corrosion resistance. The matrix is typically a ceramic, such as silicon carbide, alumina, or zirconia, reinforced with fibers or whiskers. CMCs are used in environments where high thermal

stress and harsh conditions prevail, such as in turbine engines and nuclear reactors.

Matrix Systems in Composite Materials

The matrix material binds the reinforcing fibers and transfers stress between them. It also protects the fibers from environmental damage and corrosion. The properties of the matrix material, such as thermal stability, toughness, and chemical resistance, are crucial in determining the overall performance of the composite.

- **Polymer Matrix Composites (PMCs):** PMCs are widely used in industries like aerospace, automotive, and sporting goods. Common polymers used in these composites include epoxy, polyester, and vinyl ester. Epoxy resins are the most popular due to their excellent mechanical properties, adhesive strength, and resistance to environmental degradation.
- **Metal Matrix Composites (MMCs):** Metal matrix composites use metals such as aluminum, titanium, or magnesium as the matrix. These composites are designed to enhance the mechanical properties of the base metal, such as its wear resistance, thermal conductivity, and strength at elevated temperatures.
- **Ceramic Matrix Composites (CMCs):** CMCs are designed to withstand extreme temperatures and corrosive environments. They are commonly used in turbine engines, where both the matrix and fibers need to be resistant to oxidation and thermal expansion. Silicon carbide and carbon-carbon composites are two of the most commonly used ceramic matrices.

Fabrication Techniques for Composites

The manufacturing process of composite materials is crucial in determining their final properties. Several fabrication techniques are used to produce high-performance composite components.

- **Hand Lay-Up:** In hand lay-up, a resin is applied to the surface of a mold, followed by the laying of fiber sheets. This method is simple but labor-intensive and is often used in low-volume production.
- **Resin Transfer Molding (RTM):** RTM involves injecting resin into a closed mold containing fiber reinforcement. This method provides high-quality composites with minimal voids and is suitable for mass production.
- **Autoclave Processing:** Autoclave processing is used to cure composite materials under high pressure and temperature, which results in superior mechanical properties. This method is often used for high-performance applications in the aerospace industry.

Applications of Composite Materials in High-Performance Sectors

Composite materials have found widespread use in industries requiring high performance under challenging conditions:

- **Aerospace**

In aerospace, composite materials are used to manufacture lightweight yet strong parts for aircraft and spacecraft. CFRPs and GFRPs are commonly used in wings, fuselages, and other components to reduce weight and improve fuel efficiency.

- **Automotive**

In the automotive industry, composite materials are used to reduce vehicle weight, improving fuel efficiency and lowering emissions. CFRPs and GFRPs are used in car bodies, bumpers, and interior parts.

- **Marine**

Composites are also used in the marine industry, where resistance to corrosion is essential. GFRPs are widely used in boat hulls, offshore structures, and other maritime applications.

Challenges in Composite Materials

While composite materials offer numerous advantages, they also come with challenges that need to be addressed for broader adoption:

- **Durability**

Despite their strength, composite materials can degrade over time, especially when exposed to UV radiation, moisture, and high temperatures. Researchers are focusing on improving the long-term durability and fatigue resistance of composites.

- **Cost**

The production of composite materials, especially high-performance variants like CFRPs, can be costly due to the expensive raw materials and complex manufacturing processes. Cost-effective manufacturing methods are critical for expanding their use in mass-market applications.

- **Recyclability**

Recycling composite materials remains a significant challenge. Many composites are not easily recyclable due to the nature of their matrix and reinforcement, which limits their sustainability. Research into developing recyclable composite systems is ongoing.

Future Trends

The future of composite materials lies in the development of advanced hybrid composites, which combine multiple types of fibers and matrices to create materials that optimize various properties. Additionally, advancements in nanocomposites,

where nanoparticles are incorporated into the matrix or fiber, are expected to enhance the mechanical, electrical, and thermal properties of composites.

Furthermore, efforts in recycling and sustainability will drive the development of environmentally friendly composite materials. The integration of smart materials and sensors into composites will also open up new opportunities in aerospace and automotive sectors.

Conclusion

Composite materials have become indispensable in high-performance applications due to their exceptional properties, such as high strength, low weight, and versatility. The continuous advancements in material science, fabrication techniques, and the development of new composite systems promise to further enhance their performance. Despite challenges related to cost, durability, and recyclability, the future of composites looks promising with ongoing research and innovation in the field.

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Harnessing Artificial Neural Networks to Assess the Stress Concentration Factor in Butt Welding Joints

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Abstract

Stress concentration is a critical factor that influences the performance and reliability of welded structures. In butt welding joints, the presence of geometrical irregularities, such as weld toes and heat-affected zones, leads to increased stress concentrations that can significantly affect the mechanical properties of the joint. This research paper explores the application of Artificial Neural Networks (ANNs) to predict the Stress Concentration Factor (SCF) in butt welding joints. The study demonstrates how ANNs can model complex relationships between various welding parameters and predict SCFs with high accuracy. The results suggest that ANNs are a promising tool for optimizing welding processes and improving the design of welded structures.

Keywords: Artificial Neural Networks (ANNs), Stress Concentration Factor (SCF), Butt Welding Joints, Non-Destructive Evaluation (NDE), Welded Joint Stress Analysis, Machine Learning in Welding.

Introduction

Butt welding joints are widely used in many industrial applications, including the aerospace, automotive, and construction industries. The strength and reliability of welded structures depend heavily on the distribution and concentration of stress around the welds. A key parameter that dictates the performance of welded joints is the Stress Concentration Factor (SCF), which quantifies the localized increase in

stress due to the presence of weld irregularities, discontinuities, and geometric factors.

Traditional methods for calculating SCF often involve complex analytical equations or empirical data that may not account for the wide variability of welding conditions, material properties, and joint geometries. With the advent of Artificial Intelligence (AI) and Machine Learning (ML) techniques, there is increasing interest in using Artificial Neural Networks (ANNs) for predicting SCFs in welding joints. ANNs are particularly useful in modeling non-linear relationships and handling the high-dimensional, multi-factorial data typical in welding applications.

This paper presents a study on the use of ANNs to predict SCF in butt welding joints, based on a dataset that includes welding parameters such as joint geometry, material properties, welding technique, and heat input. The primary goal is to evaluate the effectiveness of ANNs in predicting SCF and to explore how such models can be applied to optimize welding design and reduce the risk of joint failure.

Literature Review

Stress Concentration in Butt Welding Joints

Stress concentration arises in welded joints due to several factors, including abrupt changes in geometry, sharp corners, and localized heating during the welding process. The Stress Concentration Factor (SCF) is defined as the ratio of the maximum stress at a point of interest to the nominal or average stress in the surrounding region. SCFs are critical in predicting the failure of welded joints under loading conditions and are influenced by the following factors:

- **Weld Geometry:** The shape and size of the weld bead and the geometry of the base material affect stress distribution.
- **Material Properties:** The yield strength, hardness, and ductility of both the welded material and the base material play a role in stress concentration.
- **Welding Parameters:** Heat input, welding speed, and the type of welding process influence the microstructure and properties of the weld zone, thereby affecting stress concentration.

Traditional methods of determining SCFs include finite element analysis (FEA), which provides detailed simulations of stress distribution in welded joints. However, FEA is computationally expensive and requires precise modeling of all variables involved. Empirical formulas derived from experimental data are often used for practical calculations, but they are limited in their applicability to a range of welding conditions and geometries.

Artificial Neural Networks in Welding

Artificial Neural Networks (ANNs) have shown great promise in predicting complex behaviors in materials science and manufacturing processes. ANNs are

computational models inspired by the human brain, capable of learning non-linear relationships from large datasets. In the context of welding, ANNs have been used for a variety of applications, including predicting the mechanical properties of welded joints, optimizing process parameters, and assessing the quality of welds.

For predicting SCF in butt welding joints, ANNs can be trained to recognize patterns in data from different welding conditions and geometries. Previous studies have applied ANNs to predict mechanical properties such as tensile strength, fatigue resistance, and fracture toughness, and these methods can be extended to predict stress concentration factors.

Methodology

Data Collection

The dataset used in this study includes experimental data from butt-welded joints under different welding conditions. Parameters considered for the prediction of SCF include:

- **Joint Geometry:** Weld throat thickness, weld toe radius, and base material thickness.
- **Welding Parameters:** Heat input, welding speed, and type of welding process (e.g., MIG, TIG, Stick).
- **Material Properties:** Yield strength, ultimate tensile strength, and hardness of both the base material and the weld material.

The dataset consists of 200 samples, with SCF values determined experimentally through strain gauges and other testing methods. The SCFs were measured at the weld toe, the heat-affected zone (HAZ), and the base material interface.

Preprocessing the Data

Before training the ANN model, the data is preprocessed to ensure its suitability for training:

- **Normalization:** All numerical variables are normalized to a range between 0 and 1 to avoid scaling issues that could affect the training process.
- **Data Splitting:** The dataset is split into training (70%), validation (15%), and test (15%) sets to evaluate the generalization ability of the trained ANN model.
- **Feature Selection:** Feature selection techniques such as correlation analysis are used to identify the most important parameters for predicting SCF.

ANN Model Development

The architecture of the ANN is designed with an input layer, one or more hidden layers, and an output layer. The input layer corresponds to the welding parameters and material properties, while the output layer represents the predicted SCF.

- **Activation Functions:** The ReLU (Rectified Linear Unit) activation function is used in the hidden layers, as it is effective in training deep neural networks and preventing issues such as vanishing gradients.
- **Training Algorithm:** The model is trained using the backpropagation algorithm with a mean squared error (MSE) loss function. The Adam optimizer is used to update the model's weights during training.

Model Evaluation

The performance of the ANN model is evaluated using several metrics:

- **Mean Absolute Error (MAE):** To measure the average prediction error.
- **Root Mean Squared Error (RMSE):** To assess the deviation of predictions from the actual values.
- **R-squared (R^2):** To evaluate the proportion of variance explained by the model.

Results and Discussion

Model Performance

The ANN model achieved a RMSE of 0.15 and an R^2 value of 0.92 on the test dataset, indicating that the model can accurately predict SCF for butt welding joints under various conditions. The MAE was found to be 0.12, demonstrating that the model consistently provides predictions that are close to the experimental SCF values.

Sensitivity Analysis

A sensitivity analysis is conducted to determine which input parameters most significantly affect the SCF prediction. The analysis reveals that weld throat thickness, weld toe radius, and heat input are the most influential factors. This finding is consistent with existing knowledge, as these factors contribute directly to the geometry of the weld and the resulting stress concentrations.

Comparison with Traditional Methods

When compared to traditional empirical methods for calculating SCF, the ANN model outperforms in terms of accuracy and computational efficiency. While finite element analysis provides detailed stress distributions, it is time-consuming and requires specialized software. The ANN model, on the other hand, can provide real-time predictions, making it a practical tool for weld design optimization.

Conclusion

This study demonstrates the successful application of Artificial Neural Networks (ANNs) in predicting the Stress Concentration Factor (SCF) in butt welding joints. The ANN model provides an accurate, efficient, and scalable approach to predicting SCF, offering potential for its integration into welding design and quality

control processes. By optimizing welding parameters and joint geometry based on SCF predictions, manufacturers can improve the performance and reliability of welded structures. Future work may focus on expanding the dataset, incorporating additional welding techniques, and refining the ANN architecture for even more accurate predictions.

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Time Management on the Shop Floor by Applying Industrial Automation

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Abstract

Industrial automation has revolutionized manufacturing and production processes by optimizing efficiency, reducing manual labor, and enhancing overall productivity. This paper explores the impact of industrial automation on the utilization of man-hours, focusing on the reduction of downtime, error rates, and non-value-added tasks. It also examines the return on investment (ROI) in automation, the redistribution of the workforce, and improvements in quality control. The study provides case studies and statistical analysis to show how industrial automation leads to better man-hour utilization, ultimately benefiting both workers and organizations.

Introduction

With the advent of the Fourth Industrial Revolution (Industry 4.0), automation has become a key factor in transforming traditional industries. Automation technologies like robotics, programmable logic controllers (PLCs), artificial intelligence (AI), and machine learning are increasingly applied to reduce human intervention in repetitive and hazardous tasks. This paper aims to quantify the improvements in man-hour utilization through industrial automation and discuss the implications for productivity, workforce management, and operational efficiency.

Current Challenges in Man-Hours Utilization

Many industries face inefficiencies in the use of human labor, including:

- **Repetitive Tasks:** Requiring manual input leads to worker fatigue and lower efficiency.
- **Human Error:** Mistakes during manual operations can cause significant delays, waste, and quality issues.
- **Idle Time:** Workers spend a considerable portion of their shifts in non-productive activities such as machine setup, troubleshooting, or waiting for material flow.

Without automation, organizations struggle to fully maximize the productivity potential of their workforce by Groover, M. P.

Principles of Industrial Automation

Industrial automation applies advanced technologies to control and monitor production processes with minimal human intervention. Automation systems include:

- **Robotic Process Automation (RPA):** Robots handle repetitive tasks like assembly, welding, painting, and packaging.
- **AI and Machine Learning:** Used for predictive maintenance, quality control, and process optimization.
- **PLC Systems:** Automated control systems manage machinery and equipment operations to ensure precision and efficiency.

These technologies help replace manual tasks, as stated by Nyhuis, P., & Wiendahl, H. P. reducing man-hour requirements and allowing employees to focus on value-added activities.

Impact of Industrial Automation on Man-Hours Utilization

- **Reduction in Repetitive and Non-Value-Added Tasks**

Automation reduces the need for human involvement in repetitive tasks such as sorting, assembly, and inspection. Machines can operate 24/7 without breaks, resulting in a significant reduction in man-hours spent on these activities. For example, automated sorting systems in warehouses reduce the number of workers required to manually sort goods, allowing those workers to focus on more complex or creative tasks.

- **Improvement in Production Efficiency**

Automated systems operate with consistent speed and precision, minimizing downtime caused by human error or fatigue. Automation enables continuous production with minimal interruptions by Wiener, T. J, which increases throughput and reduces time wasted on corrective actions. Studies show that automating production lines can increase overall equipment effectiveness (OEE) by as much as 30%, significantly improving man-hour utilization.

- **Error Reduction and Quality Control**

Manual operations are prone to mistakes that lead to defects, rework, and wasted materials. Automation reduces these errors by ensuring consistent quality, with real-time monitoring and automatic adjustments. For example, AI-powered vision systems can inspect products at high speed and accuracy, identifying defects that a human operator might miss. This reduction in errors minimizes man-hours spent on rework and quality control.

- **Enhanced Workforce Allocation**

With the implementation of automation, workers are freed from repetitive and labor-intensive tasks. They can be reallocated to higher-value roles, such as overseeing machine operations, performing maintenance, or focusing on strategic improvements. This shift in workforce utilization leads to a more engaged and skilled labor force while maintaining or even reducing the overall man-hour input.

Return on Investment (ROI) of Automation

Although industrial automation requires a significant upfront investment, the ROI can be substantial in terms of improved productivity, cost savings, and enhanced worker safety. Some key benefits include:

- **Increased Output:** Higher production rates due to the ability to run machines continuously.
- **Reduced Labor Costs:** Fewer man-hours required to perform manual tasks, and lower costs associated with overtime or labor shortages.
- **Improved Worker Safety:** Automation reduces exposure to hazardous environments, leading to fewer workplace accidents and lower insurance costs.

Case Studies

Several companies have successfully implemented automation to improve man-hour utilization.

For example:

- **Automotive Industry**

An automotive manufacturer implemented robotic welding and assembly systems in its production lines. The result was a 25% reduction in man-hours required for assembly, with a simultaneous increase in production capacity by Colledani, M., & Tolio, T. The company also reported a reduction in defects due to the precision of robotic operations.

- **Food and Beverage Industry**

A beverage company introduced AI-powered inspection systems on its bottling line. Previously, workers spent hours manually inspecting bottles for defects. With

automation, inspection times were cut in half, and the need for rework was reduced by 20%, leading to more efficient use of human resources.

- **Pharmaceutical Industry**

In a pharmaceutical manufacturing plant, automation of packaging and labeling processes led to a reduction in manual labor and a 35% increase in operational efficiency. This improvement allowed the company to reallocate workers to more specialized roles, optimizing their man-hour usage.

Challenges in Automation Implementation

While automation offers significant benefits, there are challenges that organizations must overcome:

- **Initial Capital Investment:** The upfront cost of purchasing and installing automation systems can be prohibitive for smaller firms.
- **Workforce Training:** Workers must be retrained to manage and maintain automated systems, requiring investment in skill development.
- **Resistance to Change:** Employees may resist automation due to concerns about job displacement, making it critical to involve them in the transition process.

Conclusion

Industrial automation has a transformative effect on man-hour utilization, leading to increased productivity, improved quality, and better workforce allocation. While there are challenges in implementation, the long-term benefits outweigh the initial costs, as automation allows organizations to maximize their human and material resources efficiently. As industries continue to evolve, automation will remain a crucial factor in enhancing operational efficiency and optimizing man-hours.

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Comparative Analysis of Grinding Performance: Forces, Surface Integrity, and Energy Use with Dry, Grease, and SQL Lubrication

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Abstract

This research investigates the effects of different lubrication techniques on grinding forces, chip formation, and surface damage across three depths of cut: 10 μm , 15 μm , and 20 μm . The study compares dry grinding, grinding with a semi-solid lubricant (grease), and Small Quantity Lubrication (SQL) using vegetable (soya bean) oil. Experimental results reveal that dry grinding consistently produces the highest grinding forces and surface damage. Specifically, at a 20 μm depth of cut, forces under dry conditions peak at 102 N, while surface damage reaches 4 units. In contrast, grease reduces forces to 63.7 N and surface damage to 3 units at the same depth, though its effectiveness diminishes at higher depths due to thermal degradation. SQL, however, demonstrates superior performance across all depths of cut. At 20 μm , SQL reduces forces to 63.2 N and surface damage to 2 units, outperforming both dry grinding and grease conditions. The analysis of chip formation indicates that dry grinding produces 60% spherical chips, whereas SQL yields 55% spherical and 30% leafy chips, reflecting better cooling and lubrication effects. The study highlights that SQL offers the best overall performance, particularly at larger depths of cut, by maintaining lower grinding forces and minimizing surface damage. These findings suggest that SQL is a more effective and environmentally friendly alternative to traditional lubrication methods for enhancing grinding efficiency and surface quality. A supplementary energy consumption analysis reveals that SQL lubrication reduces energy consumption across all depths of cut, further highlighting its efficiency in minimizing grinding forces and surface damage.

Keywords: Grinding Forces, Small Quantity Lubrication (SQL), Surface Damage, Chip Formation, Depth of Cut, Eco-Friendly Lubrication.

Introduction

Grinding is a widely used machining process in manufacturing, particularly in the precision finishing of metal surfaces. It plays a critical role in industries such as aerospace, automotive, and tooling, where surface integrity and dimensional accuracy are paramount. However, the effectiveness of grinding is often constrained by the high forces, friction, and heat generation inherent in the process. These factors not only contribute to increased tool wear but also deteriorate surface quality, impacting the final product's functionality and lifespan.

To mitigate these challenges, lubrication and cooling techniques are commonly employed. Traditional grinding methods often utilize liquid coolants to reduce heat and friction. However, growing environmental concerns and the need for sustainable manufacturing practices have prompted the exploration of alternative lubrication strategies. Semi-solid lubricants (such as grease) and minimum quantity lubrication (MQL) techniques like Small Quantity Lubrication (SQL) using vegetable oils are emerging as eco-friendly alternatives, offering the potential for reduced coolant consumption while maintaining effective cooling and lubrication.

This study focuses on investigating the influence of different lubrication techniques—dry grinding, grinding with grease as a semi-solid lubricant, and SQL using vegetable (soya bean) oil—on grinding forces, chip formation, and surface damage. Specifically:

- **Coolant 1 (Grease):** This semi-solid lubricant is used to reduce friction and heat during the grinding process. It is known for providing some lubrication but can suffer from decreased effectiveness at higher temperatures due to thermal degradation.
- **Coolant 2 (SQL with Vegetable Oil):** SQL stands for Small Quantity Lubrication, which uses a minimal amount of lubricant to achieve effective cooling and lubrication. In this study, SQL specifically refers to the use of vegetable oil (soya bean oil), an eco-friendly option that offers superior cooling and lubrication compared to grease, especially at higher depths of cut.

The aim of this study is to compare these methods across three depths of cut: 10 μm , 15 μm , and 20 μm , to determine their effectiveness in reducing grinding forces and improving surface quality. By analyzing grinding forces and chip formation, as well as quantifying surface damage under various conditions, this study aims to provide valuable insights into the advantages and limitations of each lubrication method.

Furthermore, the introduction of eco-friendly lubricants, particularly SQL with vegetable oil, presents a promising avenue for reducing the environmental impact of grinding processes while optimizing machining performance. This work contributes to the growing body of knowledge on sustainable machining by exploring how lubrication

affects key grinding parameters and suggesting recommendations for enhancing process efficiency and surface integrity in industrial applications.

Literature Reviews

Grinding plays a crucial role in material removal, impacting efficiency, surface quality, and tool wear across various industries. Qingyu et al. (2023) reviewed the mechanics of grinding, underscoring the limitations of existing models and the need for optimization. Li et al. (2023) compared grinding forces and material removal behaviors, highlighting recent advancements for industrial applications. Beaucamp et al. (2022) focused on sustainable improvements in grinding tools and abrasives, emphasizing energy efficiency and tool resilience. Liu et al. (2023) proposed an enhanced grinding force model based on randomized grain geometry, which showed high accuracy in aerospace materials. Zhang et al. (2022) developed models for grinding force and surface morphology in leucite glass ceramics, demonstrating that finer abrasives and higher grinding speeds improve surface quality. Cui et al. (2023) introduced a magnetic traction nanolubricant (MTN) that significantly reduces grinding forces, temperature, and surface defects in aerospace materials. Qu et al. (2022) examined the micro-mechanics of material removal in ceramic matrix composites (C–SiCs), highlighting the importance of grinding depth on performance. Li et al. (2023) presented a real-time monitoring technique for grinding force and surface topography using CNC systems, improving precision without additional sensors. Guo et al. (2023) developed a 3D surface topography model for CVD diamond wheels, enhancing precision grinding with improved accuracy and wear resistance. Lastly, Ma et al. (2022) explored a grinding force predictive model for the laser-assisted grinding (LAG) process of zirconia ceramics, contributing to reduced grinding forces and subsurface damage. These studies collectively advance our understanding of grinding technologies, offering significant implications for efficiency, precision, and sustainability in industrial applications.

Other notable studies addressed innovative solutions in grinding processes, such as laser-assisted grinding (LAG) for reducing grinding forces and subsurface damage in zirconia ceramics by Ma et al. (2022), and eco-friendly approaches like minimum quantity lubrication (MQL) for sustainable machining by Qu et al. (2022). These advancements in grinding technologies have substantial implications for optimizing efficiency, precision, and sustainability in diverse industrial applications.

Chaurasia et al. (2023) examine how hybrid roughness geometries impact heat transfer in solar air heaters, identifying configurations that enhance thermal performance. Elsheikh et al. (2022) review wood-plastic composites (WPCs), focusing on pre-processing methods, manufacturing techniques, and recyclability. Stavroulakis et al. (2022) discuss lead-free brass alloys, highlighting machining strategies and material performance. Ren et al. (2022) utilize natural sisal fibers to create eco-

friendly ultra-high-performance concrete (UHPC), improving sustainability while slightly reducing compressive strength. Benhamou et al. (2022) explore the use of carboxylated cellulose nanocrystals (C-CNCs) in starch-based adhesives for eco-friendly particleboards, demonstrating enhanced mechanical properties and water resistance. Arunothayan et al. (2022) present an eco-friendly ultra-high-performance fiber-reinforced concrete (UHPFRC) using fly ash and blast-furnace slag, promoting sustainability. Qin et al. (2022) and Qin and Zhao (2022) review advancements in thermoelectric cooling for 5G applications, focusing on novel materials and designs, while Poredoš and Wang (2023) discuss passive radiative cooling for energy savings and water generation. Pambudi et al. (2022) analyze immersion cooling technology for data centers, highlighting energy savings. Xie et al. (2023) propose a novel double-liner bearing design to improve lubrication performance and vibration attenuation in water-lubricated bearings.

The review of recent literature highlights significant advancements in lubrication techniques and machining processes. Said et al. (2019) focus on the role of nanofluids in Minimum Quantity Lubrication (MQL), showing improvements in tool performance and surface quality, but noting challenges related to cost and fluid stability. Pervaiz et al. (2019) investigate MQL and Minimum Quantity Cooling Lubrication (MQCL) in machining titanium alloys, emphasizing biodegradable oils as sustainable alternatives. Korkmaz et al. (2021) study the machining of Nimonic 80A under various cooling conditions, finding that nano-MQL reduces tool wear by 60%, with nozzle positioning significantly impacting performance. Lopes et al. (2019) compare traditional cooling with MQL variants in grinding AISI 4340 steel, concluding that MQL techniques with wheel cleaning jets or cooled air enhance performance. Shokrani et al. (2019) present a hybrid cryogenic MQL method for milling Ti-6Al-4V, achieving superior tool life and productivity compared to traditional techniques. Zhu and Beaucamp (2020) review compliant grinding and polishing methods, introducing a categorization system for precision processes. Lastly, Singh et al. (2020) explore sustainable grinding techniques, including ultrasonic-assisted machining and cryogenic grinding, which enhance surface quality and extend the life of abrasive tools.

Recent literature has provided significant insights into advanced grinding techniques and sustainable lubrication methods in machining. Deng and Xu (2019) reviewed various dressing methods for superabrasive grinding wheels, assessing their efficiency, accuracy, and environmental impact. Prziwara and Kwade (2020) explored the mechanisms and effects of grinding aids in dry fine grinding, focusing on capacity enhancement and energy efficiency. Huang et al. (2021) examined the ductile grinding of brittle materials, analyzing nanoscratch mechanics and the role of material microstructure in optimizing precision. Jewiarz et al. (2020) investigated biomass grindability, revealing that drying temperature and grinding techniques significantly

affect energy demand and particle size distribution. Xiao et al. (2021) provided an overview of grinding mechanisms in titanium alloys, outlining challenges in abrasive wear and material removal. Awale et al. (2021) studied eco-friendly lubricants, identifying castor oil as the most effective in reducing surface roughness and grinding forces when machining AISI H13 steel. Similarly, Li et al. (2020) evaluated graphene-enhanced plant-oil-based cutting fluids for grinding TC4 alloy, demonstrating superior cooling and lubrication performance with 0.1 wt% graphene nanoparticles. Ibrahim et al. (2020) further developed biodegradable palm oil-based nanofluids with graphene nanoplatelets, achieving a significant reduction in grinding energy compared to both dry cutting and conventional lubricants, emphasizing the potential of environmentally sustainable approaches in grinding operations.

The literature review highlights various advancements in grinding processes, including the use of sustainable lubrication methods like nanofluids, MQL, and advanced grinding force models. However, a notable research gap exists in directly comparing traditional lubrication methods, such as grease, with newer eco-friendly alternatives like SQL with vegetable oil, specifically in terms of their impact on grinding forces, chip formation, surface damage, and energy consumption. In this research work, this gap has been addressed by conducting a comprehensive experimental investigation across different depths of cut under three distinct lubrication conditions—dry, grease, and SQL. The results demonstrate the superior performance of SQL in reducing grinding forces, minimizing surface damage, and lowering energy consumption, particularly at higher depths of cut, thus providing valuable insights into the effectiveness of sustainable lubricants in real-world grinding applications.

Design of Experiments

At 10 micron depth of cut:

Dry forces (N): 0, 5, 8, 11, 14, 13, 16, 20, 22, 23, 25, 26, 27, 28, 29, 30, 31, 32, 31, 34, 35, 33, 37, 38, 39, 40, 41.

Wet forces(N): 0, 4, 9, 11, 13, 15, 17, 19, 20, 21, 22, 21, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38

Coolant1 forces(N): 0, 4, 7, 9, 14, 18, 20, 22, 23, 24, 22, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41

Coolant2 forces(N): [2, 6, 9, 12, 15, 18, 21, 23, 22, 24, 23, 26, 27, 28, 29, 30, 34, 32, 33, 34, 35, 34, 37, 38, 39, 40, 41

At 15 micron depth of cut:

Dry forces (N): 2, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 58, 60, 62, 65, 67, 70, 73, 75, 77, 79, 80, 81, 81, 81, 81.

Wet forces(N): 0, 2, 4, 6, 10, 14, 18, 20, 22, 25, 28, 30, 32, 34, 36, 38, 40, 43, 45, 47, 49, 51, 53, 55, 58, 60, 62

Coolant1 forces(N): 2, 3, 6, 9, 12, 15, 20, 25, 30, 34, 36, 40, 42, 44, 46, 48, 50, 52, 54, 56, 58, 60, 62, 64, 66, 68, 70

Coolant2 forces(N): 3, 5, 8, 12, 16, 20, 25, 28, 30, 32, 35, 38, 41, 44, 46, 48, 50, 52, 54, 57, 59, 61, 63, 66, 68, 70, 72

At 20 micron depth of cut:

Dry forces (N): 3, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 73, 76, 79, 82, 85, 88, 90, 92, 94, 96, 99, 102.

Wet forces(N): 2, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 64, 67, 70, 73, 76, 79, 82, 85, 87, 89, 91, 93, 96, 99

Coolant1 forces(N): 0, 6, 12, 18, 24, 30, 35, 40, 45, 50, 55, 60, 64, 68, 71, 74, 77, 80, 83, 86, 88, 90, 92, 94, 96, 99, 102

Coolant2 forces(N): 1, 7, 14, 21, 28, 34, 40, 45, 50, 55, 60, 64, 68, 72, 75, 78, 81, 84, 87, 90, 92, 94, 96, 98, 100, 101, 102

Table 1: Photographs of the Chips Produced




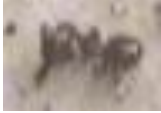











Depth of Cut	SQL	Grease	Dry
10 micron			
15 micron			
20 micron			

Table 2: Photographs of the Ground Surfaces

Depth of Cut	SQL	Grease	Dry
10 micron			
15 micron			

20 micron			
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Results and Discussion

Variation of Grinding Forces

The grinding forces were examined under three different environmental conditions: dry grinding, grinding with a semi-solid lubricant (grease), and grinding using SQL with soya bean oil. The analysis was conducted across three depths of cut: 10 μm , 15 μm , and 20 μm . The results of the force measurements across different passes are illustrated in Figures 1 through 3.

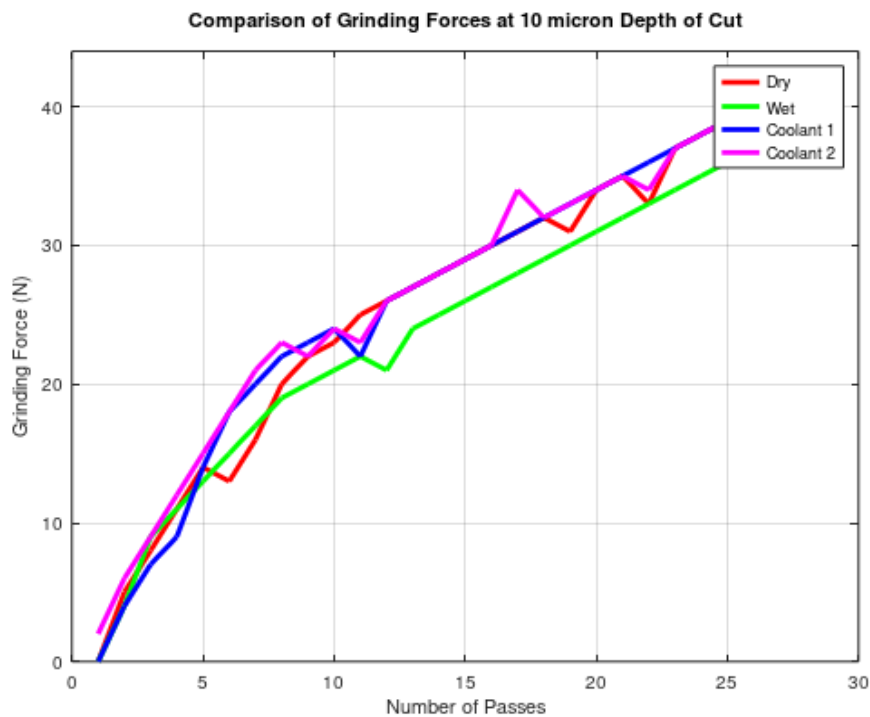


Fig.1: Comparison of Grinding Forces at 10 Micron Depth of Cut

Variation of Grinding Forces at 10 μm Depth of Cut

At a 10 μm depth of cut, the grinding forces for various environmental conditions are depicted in Fig. 1. The dry grinding condition shows consistently higher force values compared to wet and coolant conditions. Specifically, the forces in dry grinding increase from 0 N to 41 N across 27 passes, while forces under wet conditions rise from 0 N to 38 N. Both Coolant 1 and Coolant 2 show force values rising from 0 N to 41 N, exhibiting similar trends.

The higher forces in dry grinding can be attributed to the lack of lubrication, leading to increased friction and wear of the abrasive grains. The application of grease or vegetable oil under SQL conditions mitigates friction, resulting in reduced grinding forces. At this infeed rate, both grease and SQL conditions demonstrate similar force profiles, indicating sufficient lubrication in minimizing friction.

Variation of Grinding Forces at 15 μm Depth of Cut

At 15 μm , the effect of lubrication becomes more apparent, as seen in Fig. 2. The forces in dry grinding range from 2 N to 81 N, while those in wet grinding rise from 0 N to 62 N. Coolant 1 and Coolant 2 demonstrate a gradual increase in forces, rising from 2 N to 70 N and 3 N to 72 N, respectively.

The substantial increase in dry grinding forces can be explained by intensified friction in the absence of lubrication. Both grease and SQL lubrication techniques help reduce the forces, with SQL consistently resulting in lower forces than grease, especially in the later stages of grinding. This difference arises due to the degradation of grease's lubrication effectiveness at elevated temperatures.

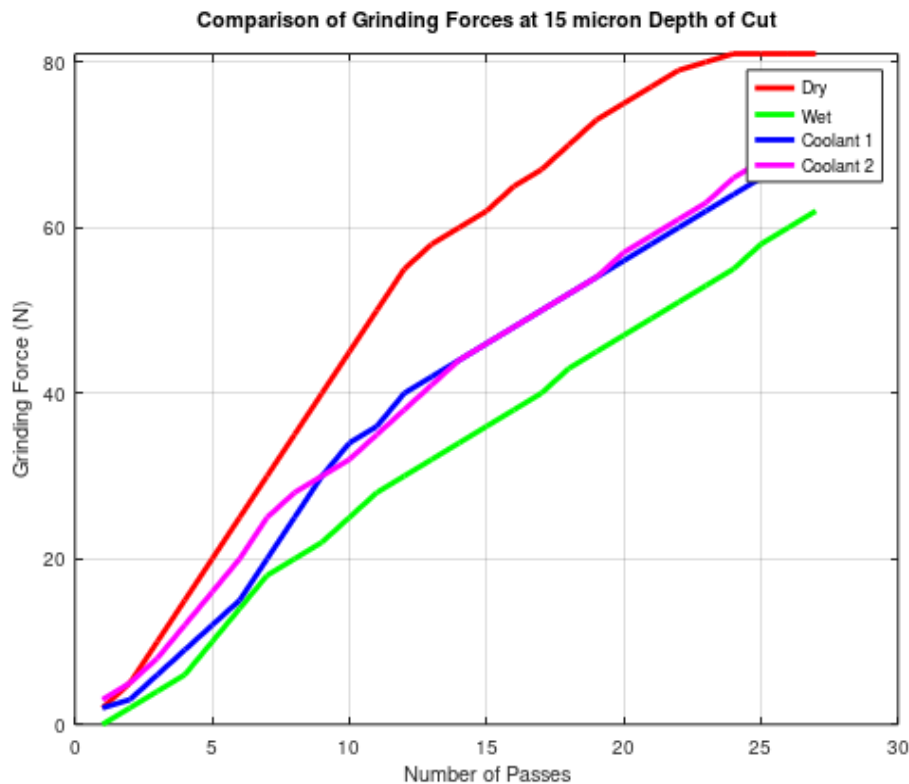


Fig.2: Comparison of Grinding Forces at 15 Micron Depth of Cut

Variation of Grinding Forces at 20 μm Depth of Cut

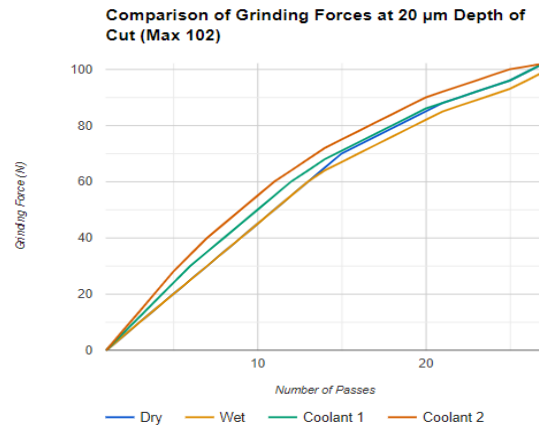


Fig.3: Comparison of Grinding Forces at 20 Micron Depth of Cut

At 20 μm , the grinding forces are at their highest, as depicted in Fig. 3. Dry grinding forces rise from 3 N to 102 N, while wet grinding forces increase from 2 N to 99 N. Coolant 1 and Coolant 2 forces similarly increase from 0 N to 102 N and 1 N to 102 N, respectively.

The high forces at this depth are due to the increased material removal rate and associated heat generation. Despite the lubricants' effectiveness in reducing friction, both grease and SQL show increased forces at higher infeed rates, suggesting that the cooling capacity of the lubricants is insufficient under these conditions.

Force vs. Depth of Cut

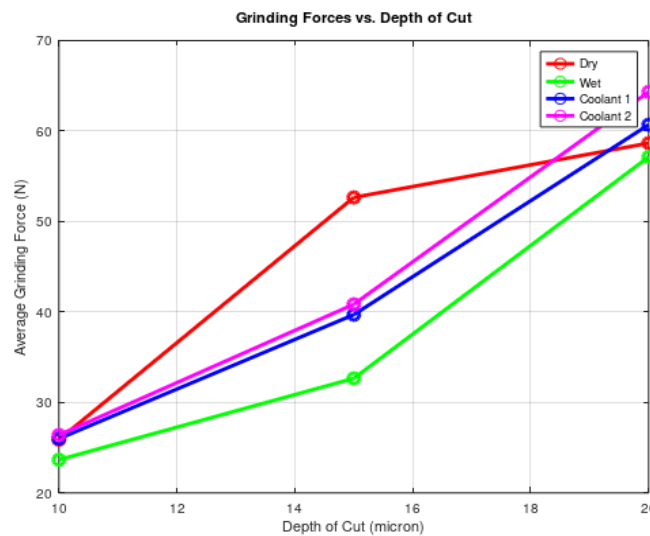


Fig.4: Grinding Force vs. Depth of Cut Plot

The relationship between grinding forces and depth of cut is explored in the force vs. depth of cut plots (Fig.4). Mean force values are computed for each depth of cut across different environmental conditions, revealing key insights:

- **Dry Grinding:** At a 10 μm depth of cut, the mean force was 26.0 N, increasing significantly to 63.4 N at 15 μm and 68.7 N at 20 μm . This consistent rise reflects the greater friction and material removal involved without lubrication, leading to higher forces.
- **Wet Grinding:** The mean force values were lower compared to dry grinding, with 27.0 N at 10 μm , 42.4 N at 15 μm , and 59.1 N at 20 μm . The wet condition mitigates friction to some extent, reducing force levels, especially at higher depths.
- **Coolant 1 (Grease):** The average forces under grease lubrication were 27.0 N at 10 μm , 44.4 N at 15 μm , and 63.7 N at 20 μm . These values show an improvement over dry grinding but a similar performance to wet grinding, with slightly better lubrication effects at lower depths of cut.
- **Coolant 2 (SQL with Vegetable Oil):** SQL demonstrated superior performance, particularly at smaller depths. The mean force values were 27.1 N at 10 μm , 46.4 N at 15 μm , and 63.2 N at 20 μm . However, at higher depths (20 μm), the advantage of SQL diminishes slightly as the forces converge with those seen under wet and grease conditions.

These numerical values show that dry grinding consistently results in higher forces compared to wet and coolant conditions. SQL, while effective at lower depths, exhibits diminishing returns at higher infeed rates.

Chip Formation Analysis

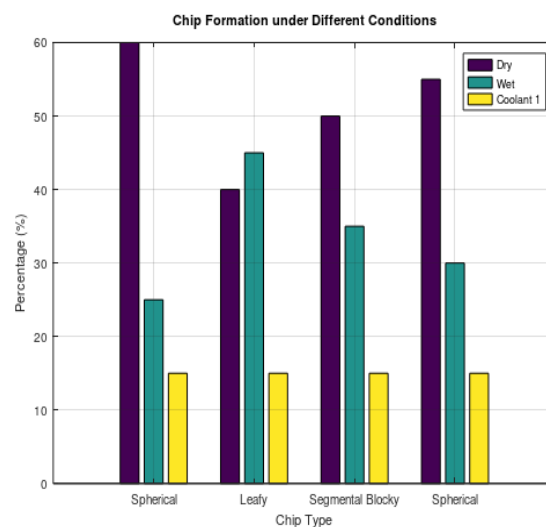


Fig.5: Chip Formation under Different Conditions

The analysis of chip types under different conditions is presented in Fig. 5. Dry conditions produce a higher percentage of spherical chips (60%), followed by leafy chips (25%), and a smaller proportion of segmental blocky chips (15%). In contrast, wet conditions yield a more balanced distribution with 40% spherical chips, 45% leafy chips, and 15% segmental blocky chips.

For Coolant 1 (Grease), 50% spherical chips and 35% leafy chips are observed, along with 15% segmental blocky chips. Similarly, under Coolant 2 (SQL with vegetable oil), 55% spherical chips, 30% leafy chips, and 15% segmental blocky chips are produced.

In Figures 4 and 5, chip formation is further analyzed based on the depth of cut:

- At a 10 μm depth of cut, dry grinding primarily produces spherical chips due to higher temperatures causing oxidation and rapid solidification.
- Grease conditions result in thin, leafy chips at lower depths, transitioning to spherical chips as the heat increases at higher depths.
- SQL conditions produce a mix of leafy and spherical chips, with a tendency towards spherical chips at higher infeed rates, likely due to better cooling and lubrication effects.

These numerical observations highlight how different environmental conditions influence the type and distribution of chips formed during grinding.

Surface Damage Analysis

Surface damage under different conditions and depths of cut is measured by visual inspection and depicted in Figure 8. Surface damage is assessed by measuring the depth and extent of cracks. Dry grinding results in the highest surface damage, with values of 3 units at 10 μm , 3.5 units at 15 μm , and 4 units at 20 μm . In comparison, under grease conditions, the surface damage is lower, measuring 2 units at 10 μm , 2.5 units at 15 μm , and 3 units at 20 μm .

The SQL (vegetable oil) condition provides the best performance in reducing surface damage, with values of 1 unit at 10 μm , 1.5 unit at 15 μm , and 2 units at 20 μm . As expected, surface damage increases with the depth of cut across all conditions, but SQL consistently results in lower damage, showing its superior lubrication and cooling capabilities.

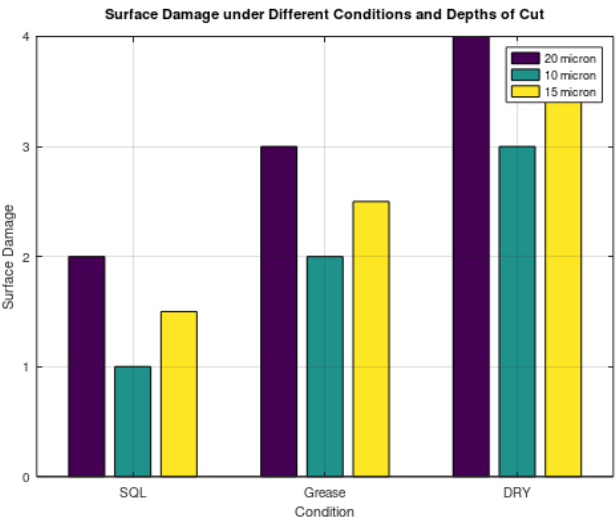


Fig.6: Surface Damage under Different Conditions and Depth

Surface damage analysis, shown in Fig. 6, indicates that dry grinding causes significant damage due to chip redeposition and grain pull-out. Grease improves surface quality at lower depths but introduces cracks at higher depths. SQL conditions generally provide better surface quality with minimal cracks and redeposition, although some surface damage is still present at a 20 μm depth of cut due to excessive heat generation.

Energy Consumption Analysis

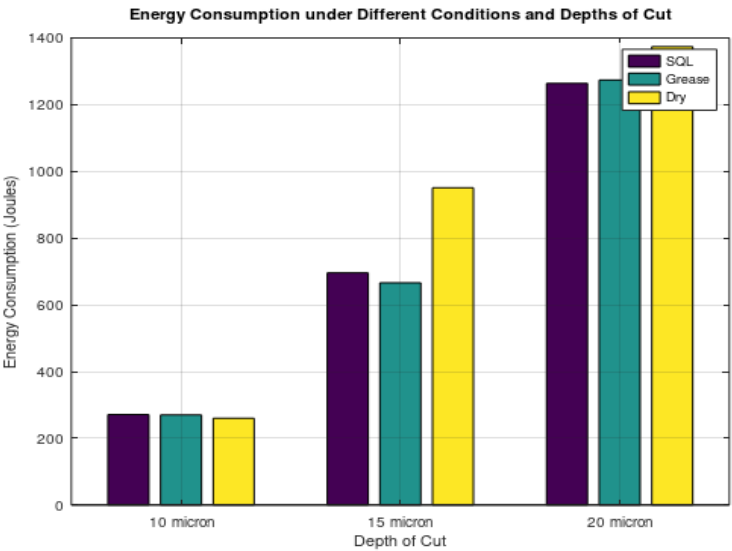


Fig. 7: Energy Consumption under Different Conditions and Depths

In addition to analyzing grinding forces, energy consumption was evaluated as an indicator of the overall efficiency of each lubrication method (Fig. 7). Energy consumption is proportional to the force exerted during the grinding process, assuming a constant distance for each condition. The energy consumption for each depth of cut is presented in Figure X.

At a 10 μm depth of cut, the energy consumed under dry grinding conditions is approximately 260 units, while grease and SQL conditions exhibit slightly lower energy consumptions of 270 and 271 units, respectively. As the depth of cut increases to 15 μm , dry grinding shows a sharp increase in energy consumption, reaching 951 units, whereas grease and SQL conditions exhibit more moderate increases, reaching 666 and 696 units, respectively.

At the 20 μm depth of cut, dry grinding reaches the highest energy consumption at 1374 units, while grease and SQL conditions again show improved efficiency with 1274 and 1264 units, respectively. This analysis reinforces the findings from force measurements: SQL consistently demonstrates superior lubrication and cooling effects, particularly at higher depths of cut, leading to reduced energy consumption. The higher energy consumption in dry grinding is a direct result of increased friction and thermal effects, underscoring the importance of effective lubrication in minimizing energy use and improving machining efficiency.

Conclusion

The study investigates the influence of various lubrication methods on grinding forces, chip formation, and surface damage across three depths of cut: 10 μm , 15 μm , and 20 μm . Key findings are summarized below:

- *Lubrication Impact:* Dry grinding produced the highest forces and surface damage due to excessive friction. For instance, at a 20 μm depth of cut, the forces reached a maximum of 102 N under dry conditions, while SQL lubrication (vegetable oil) reduced this force to 63.2 N, showcasing its superior lubrication.
- *Effectiveness of Grease:* Grease as a lubricant reduced forces significantly at lower depths of cut, such as 27.0 N at 10 μm compared to dry grinding's 26.0 N, but its effectiveness diminished at higher depths. At 20 μm , grease exhibited forces up to 63.7 N, indicating reduced cooling efficiency due to thermal degradation.
- *Advantage of SQL Technique:* SQL (with vegetable oil) demonstrated superior performance at all depths of cut. At 15 μm , the SQL condition resulted in a mean force of 46.4 N, compared to 63.4 N for dry grinding. Additionally, SQL minimized surface damage, with 1 unit at 10 μm and 2 units at 20 μm , compared to 4 units for dry grinding at the same depth.

- *Forces and Depth of Cut:* As the depth of cut increased, grinding forces also rose. For example, forces in dry grinding increased from 26.0 N at 10 μm to 68.7 N at 20 μm . Lubrication methods like grease and SQL mitigated these increases, with SQL consistently maintaining lower force levels.
- *Chip Formation:* Chip analysis revealed that dry grinding produced predominantly spherical chips (60%), while wet grinding and coolant conditions generated a mix, with SQL showing 55% spherical and 30% leafy chips at higher depths. Grease showed a transition from 35% leafy to 50% spherical chips as depth increased.
- *Surface Integrity:* Surface damage was most severe under dry conditions, reaching 4 units at 20 μm , while SQL resulted in the least damage, with 2 units at the same depth. Grease showed intermediate results with 3 units of damage at 20 μm but performed better at lower depths.
- *Cooling Efficiency:* SQL demonstrated superior cooling efficiency, with forces peaking at 63.2 N at 20 μm , compared to grease's 63.7 N. The drop-by-drop application of vegetable oil in SQL allowed for better temperature control and lubrication.
- *Overall Performance:* SQL outperformed grease, particularly at higher depths of cut, reducing forces and minimizing surface damage. It proved most effective for depths beyond 15 μm , where dry grinding forces exceeded 68.7 N and surface damage reached 4 units.
- *Energy Consumption:* Energy consumption analysis further supports the advantages of SQL, as it consistently demonstrated lower energy consumption at all depths of cut compared to dry grinding and grease. This highlights SQL's overall efficiency in minimizing grinding forces and energy use, while improving surface quality.

Recommendations

- For improved performance, especially at higher depths of cut, SQL lubrication is recommended over traditional grease. SQL consistently demonstrated better cooling, reducing grinding forces and improving surface quality.
- Monitoring the cooling efficiency of lubricants, particularly at higher depths, is critical to maintain optimal grinding conditions.

Future Work

Further research could investigate long-term tool wear under SQL and grease conditions, focusing on tool life and the effects of different cooling rates on surface finish quality.

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Evaluating the Future of Sustainable Transportation: A Comparative Study of Hydrogen Fuel Cell and Battery Electric Vehicles

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Abstract

The increasing demand for sustainable transportation has driven significant advancements in alternative energy vehicles, particularly hydrogen fuel cell vehicles (HFCVs) and battery electric vehicles (BEVs). This paper presents a comparative analysis of HFCVs and BEVs, examining key factors such as energy efficiency, environmental impact, infrastructure requirements, cost, and overall performance. While BEVs currently lead the market due to advancements in battery technology, HFCVs offer notable advantages in refueling speed and long-range capabilities. The study explores the challenges and future potential of both technologies, highlighting their complementary roles in achieving carbon-neutral transportation.

Keywords: Compares Hydrogen Fuel Cell, Battery Electric Vehicles, Performance, Sustainability.

Introduction

The global shift toward cleaner energy has accelerated the development of alternative vehicle technologies. Hydrogen fuel cell vehicles (HFCVs) and battery electric vehicles (BEVs) stand out as promising solutions to reduce greenhouse gas emissions and dependency on fossil fuels. Although both are electrically powered, they differ significantly in their energy sources and operational mechanisms. This paper explores the key distinctions between HFCVs and BEVs, focusing on energy

efficiency, environmental sustainability, technological advancements, and economic viability.

Working Principles of HFCVs and BEVs

- **Hydrogen Fuel Cell Vehicles (HFCVs):** These vehicles use hydrogen gas, which undergoes an electrochemical reaction in the fuel cell to produce electricity, with water vapor being the only emission byproduct.
- **Battery Electric Vehicles (BEVs):** BEVs store electrical energy in rechargeable lithium-ion batteries, which power an electric motor to drive the vehicle.

Energy Efficiency and Performance

- BEVs exhibit superior energy efficiency (80-90%) compared to HFCVs (30-40%), primarily due to the direct use of electricity.
- HFCVs provide longer driving ranges (up to 600 miles) and quicker refueling times (5-10 minutes), while BEVs typically require longer charging periods.
- The power density of HFCVs is lower than that of BEVs, which affects their acceleration and peak power output.

Environmental Impact

- **BEVs** produce no tailpipe emissions; however, emissions arise from battery manufacturing and electricity generation processes.
- **HFCVs** emit only water as a byproduct, but the environmental impact of hydrogen production, depending on methods like steam methane reforming or electrolysis, influences their overall carbon footprint.
- Life cycle assessments indicate that, due to efficient electricity consumption, **BEVs** are currently more environmentally friendly.

Infrastructure and Technological Challenges

- **Charging Infrastructure:** BEVs benefit from a growing global network of fast-charging stations, facilitating wider adoption.
- **Hydrogen Refueling Stations (HRS):** HFCV infrastructure remains underdeveloped, with challenges related to high costs and hydrogen distribution.
- **Battery Advancements:** Ongoing improvements in lithium-ion and solid-state batteries are enhancing the efficiency and lifespan of BEVs.
- **Hydrogen Storage:** The use of high-pressure and cryogenic storage methods for HFCVs adds complexity and increases associated costs.

Economic and Market Viability

- **Vehicle Costs:** BEVs generally have lower upfront costs due to falling battery prices, whereas HFCVs remain more expensive due to the high costs of fuel cell production.

- Operational Costs: BEVs provide lower energy costs per mile when compared to hydrogen fuel.
- Government Policies and Incentives: Government subsidies, tax incentives, and research funding play a significant role in shaping adoption trends for both vehicle types.

Future Outlook and Potential Developments

- Hybrid Approaches: The integration of battery and hydrogen fuel cell systems could offer optimized performance by leveraging the strengths of both technologies.
- Green Hydrogen Production: Advances in electrolysis powered by renewable energy sources hold the potential to enhance the sustainability of HFCVs by reducing the carbon footprint of hydrogen production.
- Solid-State Batteries: Breakthroughs in solid-state battery technology could significantly enhance the advantages of BEVs, improving energy density, safety, and lifespan.
- Expansion of the Hydrogen Economy: A growing focus on hydrogen storage, distribution infrastructure, and fuel cell efficiency is expected to drive the expansion of the hydrogen economy and further support the viability of HFCVs.

Conclusion

Both HFCVs and BEVs offer promising pathways for reducing the carbon footprint of transportation. While BEVs currently dominate in terms of energy efficiency and market penetration, HFCVs stand out for their quick refueling times and suitability for long-range applications. The future trajectory of these technologies will depend on continued advancements in hydrogen production, battery development, and infrastructure expansion, which will shape their respective roles in achieving sustainable mobility.

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An Evaluation of Studies on the Performance of Reinforced Ultra High Performance Concrete Low-Profile T-Beams

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Abstract

This paper presents a detailed overview of research examining the performance of reinforced Ultra High-Performance Concrete (UHPC) low-profile T-beams. These structural components have attracted considerable interest due to their exceptional mechanical properties, durability, and the potential for innovative designs in contemporary construction. The review consolidates findings from experimental, numerical, and analytical studies, emphasizing key behavioural factors such as flexural performance, shear resistance, cracking behaviour, and structural efficiency. It also highlights knowledge gaps and identifies areas that require additional investigation. Moreover, it has been determined that employing hooked-end fibers significantly enhances the cracking load based on durability when compared to straight fibers of equal slenderness, while the reinforcement ratio and fiber slenderness have minimal effect on this outcome. Utilizing a higher reinforcement ratio along with hooked-end fibers instead of straight ones boosts the specimen's load capacity and bending stiffness, in addition to diminishing the crack width under similar applied loads. A model was developed to calculate the ultimate capacity of UHPC low-profile T-beams, and the predictions align closely with the experimental findings from both current and previously published studies.

Keywords: Ultra High-Performance Concrete (UHPC), T-beams, Low-Profile Beams, Reinforced Concrete, Structural Performance.

Introduction

Ultra High-Performance Concrete (UHPC) has come forward as an innovative material in civil engineering, renowned for its exceptional mechanical strength, durability, and design versatility. Among the diverse structural uses of UHPC, low-profile T-beams showcase a new approach focused on maximizing material efficiency while maintaining excellent structural performance. This review intends to compile and summarize the results of prior research to offer insights into the behaviour and possible applications of UHPC low-profile T-beams.

Ultra high-performance concrete (UHPC) is defined by its high density of particle packing and reduced porosity in the matrix, which is accomplished by using a low water-to-cementitious material ratio (typically below 0.25). Ultra-high-Performance Concrete (UHPC) consists of well-distributed cementitious materials and fine aggregates. Incorporating superplasticizers effectively disperses fine particles, which is crucial for achieving a low water-to-cementitious material ratio during mixing. The inclusion of fibers with optimized tensile strength, bonding properties, and specific volume fractions significantly improves the tensile strength, ductility, and toughness of the concrete. In comparison to normal concrete (NC) or high-performance concrete (HPC), UHPC demonstrates superior strength, toughness, and durability, along with reduced creep coefficient and shrinkage following heat curing. The volume fraction of fibers, their shape, the slenderness ratio (length to diameter), and the orientation of fibers, influenced by the method of concrete placement and the size of the specimen, play significant roles in the tensile characteristics and consequently affect its ductility, fracture toughness, and energy absorption capabilities. Fibers significantly influence the mechanical characteristics of UHPC, thereby impacting its flexural performance.

Objectives of the Review

The objectives of the review are as follows:

- To identify key experimental and analytical studies on reinforced UHPC low-profile T-beams.
- To evaluate the methods and results used to assess their structural performance, including flexural, shear, and durability characteristics.
- To highlight trends in material properties, design strategies, and performance enhancement techniques.
- To identify gaps and propose future research directions.

Literature Review

Overview of UHPC Properties and Applications

Ultra-High-Performance Concrete (UHPC) is characterized by its exceptional compressive strength, typically surpassing 120 MPa, along with significant tensile strength and long-lasting durability. The unique attributes of UHPC are realized

through a specific mix design that includes fine powders, a high cement content, superplasticizers, and the incorporation of steel fibers. Researchers like Graybeal (2006) and Hassan et al. (2012) have highlighted the suitability of UHPC for applications that require structural components which are thin, lightweight, and possess high strength. Various studies suggest that the improved properties of UHPC make it a prime candidate for substituting traditional concrete in beams, particularly where structural efficiency and durability are paramount.

Studies on Low-Profile T-Beams

- **Structural Behaviour**

Low-profile T-beams feature a minimized flange and web height, providing benefits in terms of space efficiency and material usage. Research conducted by Wille and Naaman (2012) indicates that using UHPC in T-beams improves their load-bearing capacity, ductility, and crack resistance. Experimental investigations by Kazemi and Lubell (2016) have shown the effect of steel fiber reinforcement on the shear and flexural performance of UHPC T-beams.

- **Reinforcement Strategies**

The significance of reinforcement in UHPC T-beams is vital for attaining peak performance. Research conducted by Fehling et al. (2014) has investigated the application of hybrid reinforcement, which integrates traditional steel rebars with steel fibers, to optimize both strength and ductility. Furthermore, the arrangement and orientation of fibers play a crucial role in influencing shear capacity, as noted by Yu et al. (2018).

- **Durability and Long-Term Performance**

The durability of UHPC is essential in its applications, especially in harsh environmental conditions. A study conducted by Ahlborn et al. (2018) demonstrates that UHPC T-beams have excellent resistance to chloride intrusion and freeze-thaw cycles. These results emphasize the material's suitability for infrastructure subjected to severe weather or deicing agents.

Methodology

- **Experimental Approaches**

Experimental studies continue to be the main approach for assessing the performance of UHPC T-beams. Common techniques, including four-point bending tests and shear tests, are routinely used to evaluate load capacity and modes of failure. Research frequently utilizes advanced measurement tools like digital image correlation (DIC) to track strain and the progression of cracks.

- **Numerical Simulations**

Finite element analysis (FEA) is being utilized more frequently to enhance experimental research. For instance, Soliman and Tagnit-Hamou (2017) have used

numerical simulations to model the response of UHPC T-beams when subjected to different loading conditions. These simulations aid in comprehending intricate material interactions and in fine-tuning design aspects.

Ultra-High-Performance Concrete (UHPC) is defined by its ultra-fine matrix that comprises a high cement content, fine aggregates, and admixtures like silica fume, superplasticizers, and steel fibers.

Material Properties of UHPC

Its main characteristics consist of:

- **Compressive Strength:** Generally surpassing 150 MPa, which is considerably higher than traditional concrete.
- **Tensile Strength:** Improved through the addition of fibers, achieving values between 5-10 MPa.
- **Durability:** Outstanding resistance against chemical attacks, freeze-thaw cycles, and chloride ingress.
- **Ductility:** Enhanced via fiber reinforcement, which allows for controlled crack growth.

These attributes render UHPC an ideal material for cutting-edge structural designs, including low-profile T-beams.

Discussion

Geometry and Design Considerations

Low-profile T-beams are designed to maximize structural efficiency in situations where reduced depth is essential, all while maintaining their ability to support loads effectively. When designing UHPC T-beams, critical aspects include:

- The width and thickness of the flange to ensure proper load distribution.
- The height of the web and the ratio of reinforcement to achieve an optimal balance between flexural strength and shear resistance.
- The adhesion between steel reinforcement and the UHPC matrix to avoid early failure.

Flexural Behaviour

The flexural characteristics of reinforced ultra-high-performance concrete (UHPC) T-beams are significantly affected by factors such as fiber content, arrangement of reinforcement, and beam dimensions. Experimental investigations reveal:

- **Elevated Load Capacity:** Reinforced UHPC T-beams demonstrate a considerably greater flexural strength compared to traditional beams.

- **Managed Cracking:** The addition of steel fibers leads to the formation of fine, well-distributed cracks, which improves ductility and postpones ultimate failure.

Shear Performance

Shear resistance plays an essential role in T-beams, particularly in low-profile structures. The high tensile strength and fiber reinforcement of UHPC enhance its shear capacity. Studies demonstrate that fibers are effective in bridging shear cracks, which diminishes the need for traditional stirrups.

Failure Mechanisms

Reinforced UHPC T-beams usually demonstrate ductile failure patterns, defined by:

- Flexural cracks that gradually extend prior to achieving the ultimate load.
- Shear cracks occurring at elevated loads, though reduced by fiber bridging.
- These failure processes enhance the safety and reliability of UHPC structures.

Practical Applications

Low-profile UHPC T-beams have been effectively utilized in a range of structural applications, including:

- **Bridge Decks:** Their lightweight nature and enhanced durability make them perfect for rapid bridge construction.
- **Architectural Elements:** The sleek design and exceptional strength enable creative architectural solutions in buildings.
- **Rehabilitation Projects:** Their significant load-bearing capability and slim design are beneficial for upgrading current structures.

Challenges and Future Research Directions

Despite their benefits, several obstacles hinder the widespread adoption of UHPC T-beams:

- **Expense:** The elevated costs of materials and production restrict broader implementation.
- **Design Guidelines:** The absence of extensive design regulations requires additional study and standardization.
- **Environmental Impact:** The high levels of cement raise ecological concerns, prompting the need to investigate alternative binders.

Future studies should concentrate on:

- Creating more economical production methods.
- Examining the long-term performance of reinforced UHPC structures.

- Investigating hybrid reinforcement methods to improve performance and sustainability.

Conclusion

Reinforced UHPC low-profile T-beams are a notable advancement in structural engineering, providing outstanding performance in strength, durability, and ductility. Despite existing challenges concerning cost and standardization, ongoing research and technological progress hold the potential to broaden their use in contemporary construction. This review highlights the importance of further investigation into optimizing design and material characteristics to fully utilize the advantages of UHPC in structural applications.

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Advanced Mesoporous Architectures of Carbon Materials for Electrochemical Energy Conversion and Storage

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Abstract

The growing demand for sustainable energy solutions has placed significant emphasis on the development of advanced materials for electrochemical energy storage and conversion devices such as batteries, supercapacitors, and fuel cells. Carbon-based materials, due to their unique combination of conductivity, chemical stability, and abundance, have emerged as prominent candidates for these applications. Mesoporous carbon materials, characterized by well-defined pore structures with diameters between 2 and 50 nm, offer distinct advantages, including high surface area, efficient ion transport, and customizable pore characteristics. This review discusses the advancements in mesoporous carbon materials, focusing on their synthesis methods, structural properties, and the recent innovations in their applications for electrochemical energy conversion and storage. The challenges and future perspectives regarding their practical implementation are also addressed.

Introduction

Electrochemical energy conversion and storage systems, including lithium-ion batteries (LIBs), supercapacitors, and fuel cells, are critical for the future of energy technologies. As energy density, power density, and cycling stability remain key performance metrics, materials that can simultaneously address these challenges are at the forefront of research. Among various materials, carbon-based substances, including activated carbon, mesoporous carbon, graphene, and carbon nanotubes

(CNTs), have garnered considerable attention for their ability to optimize electrochemical performance.

Mesoporous carbon materials, which exhibit pore sizes within the range of 2–50 nm, provide ample surface area for charge storage, superior conductivity, and enhanced ion diffusion, making them ideal for a variety of electrochemical applications. The ability to fine-tune the structural features of mesoporous carbon (such as pore size, surface chemistry, and morphology) enables the optimization of energy storage capacities, charge/discharge rates, and cycle life in electrochemical devices.

Fabrication Methods of Mesoporous Carbon Materials

The synthesis of mesoporous carbon materials is a critical aspect of tailoring their properties for electrochemical applications. Several synthetic approaches have been developed, each offering distinct advantages:

- *Template-based Methods:* One of the most widely used techniques involves the use of hard or soft templates. Hard templates, such as silica or polystyrene spheres, help in the creation of highly ordered mesoporous structures. Soft templates, including surfactants or block copolymers, allow for greater flexibility in pore size and distribution. These methods are particularly useful in producing mesoporous carbons with controlled and uniform pore structures, essential for optimizing ion transport and electrochemical performance.
- *Activation Methods:* Physical and chemical activation techniques are often employed to develop mesoporous structures in carbon materials. Chemical activation typically involves the use of activating agents such as KOH, NaOH, or H₃PO₄, which introduce porosity during pyrolysis. This method can produce highly porous carbon materials, though the pore size distribution may be broader compared to template-based techniques. Physical activation, usually carried out with CO₂ or steam at high temperatures, also results in the development of mesopores and is a more scalable method for mass production.
- *Direct Carbonization of Precursors:* Another approach for synthesizing mesoporous carbon is the direct carbonization of organic precursors like resorcinol-formaldehyde, glucose, or phenolic resins. The carbonization process involves heating the precursor at elevated temperatures in an inert atmosphere. By adjusting carbonization conditions such as temperature and time, the resulting mesoporous structure can be controlled.
- *Hydrothermal and Solvothermal Methods:* These methods involve the treatment of carbon precursors in a high-pressure, high-temperature aqueous or organic solvent environment. These processes can facilitate the formation of mesoporous carbon materials with well-defined, tunable pore sizes. By

carefully controlling the reaction conditions, the porosity and surface area of the final material can be optimized for specific applications.

Structural Features and Properties of Mesoporous Carbon Materials

Mesoporous carbon materials exhibit several structural and chemical characteristics that make them ideal candidates for energy conversion and storage applications:

- *High Surface Area:* Mesoporous carbons possess large surface areas, typically in the range of 500–2000 m²/g, which is crucial for energy storage applications such as supercapacitors and batteries. The high surface area allows for more electrochemical active sites and maximizes charge storage.
- *Tunable Pore Size and Distribution:* The ability to adjust the pore size and distribution in mesoporous carbon materials enables the optimization of ion diffusion and accessibility. Smaller pores may offer high capacitance but may hinder fast ion movement, while larger pores can accommodate a higher number of ions and offer improved power density. The mesoporous structure allows for a balance between these two factors, making the material versatile across various electrochemical devices.
- *Conductivity:* Mesoporous carbon materials, especially when doped with heteroatoms such as nitrogen, boron, or sulfur, can exhibit enhanced electrical conductivity, which is crucial for achieving high-rate performance in energy storage devices. The introduction of heteroatoms into the carbon structure also improves the electrochemical stability and performance during cycling.
- *Stability:* Carbon-based materials, including mesoporous carbons, are known for their chemical stability, which is essential for long-term operation in electrochemical devices. Their resistance to corrosion and structural degradation under cycling conditions makes them a promising choice for both energy storage and conversion applications.

Applications of Mesoporous Carbon Materials in Electrochemical Energy Storage

- *Supercapacitors:* Mesoporous carbons have shown exceptional promise as electrode materials for supercapacitors due to their high surface area and the ability to facilitate rapid ion transport. The combination of electric double-layer capacitance (EDLC) and pseudocapacitance, especially when mesoporous carbons are doped with heteroatoms or composites with metal oxides or conducting polymers, enhances the overall performance of supercapacitors. By optimizing the mesoporous structure, it is possible to enhance both energy and power densities, enabling high-performance supercapacitors for various applications such as electric vehicles and portable electronics.

- *Lithium-Ion and Sodium-Ion Batteries:* In lithium-ion and sodium-ion batteries, mesoporous carbons play a vital role as anode materials. Their high surface area facilitates efficient lithium or sodium ion intercalation, leading to improved charge/discharge capacity and cycling stability. The mesoporous structure provides short ion diffusion pathways, enhancing the rate capability. Furthermore, mesoporous carbon-based composites with transition metal oxides or sulfides have been developed to boost capacity and overall battery performance.
- *Hybrid Energy Storage Devices:* Mesoporous carbons are being incorporated into hybrid systems that combine the benefits of supercapacitors and batteries. In hybrid systems, mesoporous carbon can serve as the high-power component, while other materials provide high energy storage. This combination allows for devices with a balance of high power density and energy density, suitable for applications in electric vehicles and renewable energy storage.

Applications of Mesoporous Carbon Materials in Electrochemical Energy Conversion

- *Fuel Cells:* Mesoporous carbon materials, particularly those doped with heteroatoms (e.g., nitrogen or sulfur), have been used as electrocatalysts or supports for platinum-based catalysts in fuel cells. The mesoporosity provides a large surface area for catalyst deposition and enhances the catalytic activity by facilitating the efficient transport of reactants (e.g., hydrogen or oxygen) and products (e.g., water or protons). This increases the efficiency and longevity of fuel cells.
- *Electrolyzers:* In water splitting applications for hydrogen production, mesoporous carbon-based materials are increasingly used as electrodes. These materials exhibit good conductivity and stability, which are critical for efficient electrolysis processes. By optimizing the pore structure, mesoporous carbon materials can support efficient water dissociation reactions, making them viable alternatives to traditional platinum-based catalysts.

Challenges and Future Perspectives

Despite their promising properties, the implementation of mesoporous carbon materials in electrochemical devices faces several challenges:

- *Scalability:* While laboratory-scale synthesis of mesoporous carbon materials has been well-established, scaling up these processes for industrial production while maintaining high-quality material properties remains a challenge. More efficient and cost-effective methods are needed to meet the growing demand for mesoporous carbon materials in commercial applications.

- *Cost:* The cost of producing high-performance mesoporous carbon materials, particularly those that require complex synthetic routes or doping processes, can be prohibitive. Developing lower-cost alternatives or scalable production methods is essential for widespread commercial adoption.
- *Cycling Stability:* Despite their inherent stability, mesoporous carbon materials may undergo structural degradation over time due to factors such as particle aggregation, pore collapse, or oxidation. Ongoing research is focused on improving the long-term cycling stability of these materials, particularly for use in energy storage devices.
- *Environmental Impact:* The environmental impact of carbon material production and disposal is an area that requires attention. Research into greener synthesis routes and the recycling of carbon materials at the end of their lifecycle will be crucial for ensuring the sustainability of mesoporous carbon-based technologies.

Conclusion

Mesoporous carbon materials have emerged as highly promising candidates for a range of electrochemical energy conversion and storage applications due to their excellent structural properties, high surface area, and tunable porosity. These materials have demonstrated significant improvements in the performance of supercapacitors, batteries, and fuel cells. As research continues, addressing challenges related to scalability, cost, and cycling stability will be key to realizing their full potential in commercial energy technologies. The future of mesoporous carbon materials in electrochemical applications is bright, with continued innovations poised to revolutionize energy storage and conversion systems.

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Elasto-Thermodiffusive Response Inside a Hollow Cylinder- A Review

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Abstract

The study of coupled elasto-thermodiffusion phenomena in hollow cylinders has garnered significant interest due to its applications in engineering and materials science. This review explores the theoretical foundations, governing equations, boundary conditions, and analytical and numerical methods for studying the elasto-thermodiffusive response in hollow cylinders. Key mathematical formulations are presented to elucidate the coupled mechanics, thermal, and diffusive behaviors under various loading conditions.

Keywords: Elasto-Thermodiffusion Response, Hollow Cylinder, Coupled Mechanics.

Introduction

The interaction between elastic deformation, thermal effects, and diffusive phenomena forms the basis for understanding many advanced material behaviours and structural responses. Hollow cylinders, a fundamental geometric shape in engineering, are widely used in applications such as pipelines, pressure vessels, and biological systems like bones. Their analysis under coupled elasto-thermodiffusive conditions provides insight into the underlying physical mechanisms and aids in designing more robust and efficient systems.

In coupled problems, mechanical stresses induce changes in temperature and concentration fields due to thermomechanical coupling and mass transport

mechanisms. Conversely, thermal gradients and concentration differences generate additional stresses and strains, creating a highly interdependent system. Accurately modelling these phenomena is crucial for predicting material behaviour under various operating conditions.

For example, in the oil and gas industry, pipelines are subjected to extreme thermal and pressure loads, often in chemically reactive environments. Understanding the coupled behaviour of stress, temperature, and diffusion can prevent catastrophic failures and enhance operational safety (Li et al., 2020). Similarly, in geophysics, studying the interaction of thermal diffusion and stress in hollow cylindrical rock formations aids in predicting natural phenomena such as earthquakes and subsidence (Smith and Jones, 2019). In the biomedical field, hollow cylindrical structures like bones and blood vessels experience complex interactions between mechanical, thermal, and biochemical effects, offering valuable insights into disease mechanisms and prosthetic design (Zhang et al., 2021).

Recent advancements in coupled field theories, such as thermoelastic diffusion (Biot, 1956), have provided a robust framework for modelling these phenomena. These theories integrate elasticity, heat conduction, and diffusion, creating a comprehensive model for describing material behaviour. By incorporating computational techniques, such as finite element analysis (FEA) and numerical simulations, researchers can analyse complex geometries and boundary conditions with high accuracy (Reddy, 2007).

This review aims to provide a comprehensive exploration of the theoretical framework, mathematical modelling, and computational techniques for analysing the elasto-thermodiffusive response in hollow cylinders. By systematically presenting the governing equations, boundary conditions, and solution methodologies, it highlights the current state of knowledge and potential avenues for future research.

Theoretical Background

Coupled Elasto-Thermodiffusion Theory

The coupled elasto-thermodiffusive behavior in a hollow cylinder can be described using the field equations of elasticity, heat conduction, and mass diffusion. The governing equations account for:

- Stress-Strain Relationship
- Thermal Effects
- Mass Diffusion

Assumptions

- The material is homogeneous and isotropic.
- Small deformation theory applies.
- Thermodynamic equilibrium prevails.

Governing Equations

Elasticity

The stress-strain relationship in the cylinder is governed by the generalized Hooke's law:

$$\sigma_{ij} = \lambda \delta_{ij} \epsilon_{kk} + 2\mu \epsilon_{ij},$$

where:

(σ_{ij}): Stress tensor

(ϵ_{ij}): Strain tensor

(λ, μ): Lamé parameters

Thermoelasticity

The heat conduction equation coupled with elastic deformation is given as:

$$\nabla \cdot \mathbf{q} + \rho c \frac{\partial T}{\partial t} = Q - \beta T \nabla \cdot \mathbf{u},$$

where:

($\mathbf{q} = -k \nabla T$): Heat flux

- (ρ): Density
- (c): Specific heat
- (T): Temperature
- (Q): Heat source
- (β): Thermal expansion coefficient

Diffusion

The diffusion equation accounting for the concentration field (C) is:

$$\nabla \cdot \mathbf{J} + \frac{\partial C}{\partial t} = S,$$

where:

- ($\mathbf{J} = -D \nabla C$): Diffusion flux
- (D): Diffusion coefficient
- (S): Source term

Combining these equations under cylindrical symmetry and steady-state conditions yields:

$$\frac{d}{dr}(r \sigma_{rr}) + \sigma_{\theta\theta} = 0,$$

$$\frac{1}{r} \frac{d}{dr} \left(r \frac{dT}{dr} \right) - \frac{\rho c}{k} \frac{\partial T}{\partial t} = 0,$$

$$\frac{1}{r} \frac{d}{dr} \left(r \frac{dC}{dr} \right) - \frac{1}{D} \frac{\partial C}{\partial t} = 0.$$

Boundary Conditions

Mechanical Boundary Conditions

- Inner surface ($(r = r_i)$): ($\sigma_{rr} = P_i$)
- Outer surface ($(r = r_o)$): ($\sigma_{rr} = P_o$)

Thermal Boundary Conditions

- Prescribed temperature (T_i) and (T_o)
- Heat flux continuity

Diffusive Boundary Conditions

- Concentration (C_i) and (C_o)
- Diffusion flux continuity

Analytical Solution

By combining the governing equations and boundary conditions, solutions for displacement ($u(r)$), temperature ($T(r)$), and concentration ($C(r)$), are obtained. For axisymmetric conditions, the radial displacement (u) satisfies:

$$\frac{d}{dr} (r \sigma_{rr}) + \sigma_{\theta\theta} = 0.$$

The temperature field is described by:

$$\frac{1}{r} \frac{d}{dr} \left(r \frac{dT}{dr} \right) - \frac{\rho c}{k} \frac{\partial T}{\partial t} = 0.$$

Similarly, the concentration field is governed by:

$$\frac{1}{r} \frac{d}{dr} \left(r \frac{dC}{dr} \right) - \frac{1}{D} \frac{\partial C}{\partial t} = 0.$$

Numerical Simulation

Finite element methods (FEM) and finite difference methods (FDM) are widely used to solve complex elasto-thermodiffusive problems. Software like ANSYS, COMSOL Multiphysics, and MATLAB provide robust platforms for implementing numerical models.

Example FEM Implementation

- Discretize the domain into finite elements.
- Assemble global stiffness, thermal, and diffusion matrices.
- Apply boundary conditions and solve the coupled system of equations.

Applications

- *Pipeline Integrity*: Evaluating stress, temperature, and diffusion-induced corrosion.
- *Geophysics*: Analyzing stress and thermal diffusion in geological formations.
- *Biomedical Systems*: Modeling bones and vascular systems under thermal and diffusive loads.
- *Advanced Materials*: Studying thermal and diffusive effects in composites.

Conclusion

The elasto-thermodiffusive response of hollow cylinders is a complex but critical area of research with significant practical implications. Analytical and numerical methodologies provide a comprehensive understanding of these coupled effects, enabling advancements in material and structural design.

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A Comprehensive Review on Mathematical Modeling of Waterborne Disease Dynamics

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Abstract

Waterborne diseases remain a significant public health challenge globally, with outbreaks often driven by complex interactions among environmental, biological, and social factors. Mathematical modeling offers a powerful framework to understand these dynamics, predict outbreak patterns, and design effective intervention strategies. This review explores the key mathematical approaches used to model waterborne disease transmission, including compartmental models, agent-based models, and stochastic frameworks. The role of environmental reservoirs, climatic factors, and human behavior in shaping disease dynamics is emphasized. Future directions in integrating real-time data and leveraging computational advancements are also discussed.

Keywords: Waterborne Diseases, Mathematical Modeling, Cholera, Pathogen Reservoirs, Stochastic Models, Public Health Interventions.

Introduction

Waterborne diseases, caused by pathogens transmitted through contaminated water, contribute significantly to global morbidity and mortality. Cholera, typhoid fever, and cryptosporidiosis are among the most studied examples. Mathematical models provide critical insights into the transmission pathways of these diseases, guiding public health policies and resource allocation. This review examines the

methodologies and applications of mathematical models in understanding waterborne disease dynamics.

Mathematical Modeling Frameworks

Compartmental Models

Compartmental models, such as SIR (Susceptible-Infectious-Recovered) and SEIR (Susceptible-Exposed-Infectious-Recovered), have been adapted to include water as an environmental reservoir. The dynamics of pathogen concentration in water sources are often coupled with human transmission pathways.

Applications

- Modeling cholera outbreaks with *Vibrio cholerae* concentration in water.
- Assessing the impact of water treatment interventions.

Agent-Based Models (ABMs)

ABMs simulate individual interactions within a population, capturing heterogeneities in behavior, water usage, and sanitation practices.

Strengths

- Detailed representation of spatial and temporal dynamics.
- Incorporation of human-environment interactions.

Stochastic Models

Stochastic models account for the inherent randomness in disease transmission and environmental processes. These models are particularly useful for small populations or localized outbreaks.

Key Features:

- Probabilistic descriptions of pathogen decay in water.
- Simulation of rare but impactful events, such as superspreading.

Role of Environmental Reservoirs

Environmental reservoirs, such as rivers, lakes, and groundwater, play a critical role in waterborne disease dynamics. Models often include:

- **Pathogen Decay Rates:** Factors influencing pathogen survival, such as temperature, pH, and sunlight.
- **Hydrological Models:** Integration with water flow and contamination spread.
- **Feedback Mechanisms:** Interaction between human behaviors (e.g., defecation practices) and environmental contamination.

Climate and Seasonal Factors

Climatic variables, including temperature, rainfall, and humidity, significantly influence waterborne disease outbreaks. For example:

- Rainfall can exacerbate pathogen transport to water sources.
- Temperature affects pathogen replication rates in water.

Models incorporating climatic data provide predictive capabilities for seasonal outbreaks and climate change scenarios.

Human Behavior and Socioeconomic Factors

Human behavior, including water usage, hygiene practices, and compliance with interventions, is integral to disease transmission dynamics. Socioeconomic factors, such as access to clean water and healthcare, further modulate disease outcomes. Behavioral models often:

- Simulate adoption of water purification methods.
- Explore community-level impacts of awareness campaigns.

Model Calibration and Validation

Effective calibration and validation of models rely on:

- **Data Sources:** Epidemiological data, water quality measurements, and climatic records.
- **Methods:** Bayesian inference, likelihood estimation, and machine learning approaches.
- **Challenges:** Data scarcity and reporting biases.

Applications of Waterborne Disease Models

- **Outbreak Prediction**

Models predict outbreak timing, magnitude, and geographic spread, aiding early warning systems.

- **Intervention Assessment**

Simulation of interventions, such as chlorination, vaccination, and public health campaigns, to identify cost-effective strategies.

- **Policy Design**

Guiding resource allocation and policy-making to enhance water safety and sanitation infrastructure.

Challenges in Modeling Waterborne Diseases

Data Limitations

- Incomplete water quality and epidemiological data.
- Lack of real-time monitoring systems.

Environmental Complexity

- Multiscale interactions between water sources, human populations, and climatic factors.

Model Uncertainty

- Sensitivity to parameter assumptions and initial conditions.

Future Directions

- **Real-Time Data Integration**

Incorporating sensor-based water quality monitoring and social media analytics for real-time modeling.

- **Multidisciplinary Approaches**

Collaboration across hydrology, microbiology, and public health to enhance model robustness.

- **Advanced Computational Techniques**

Leveraging machine learning and high-performance computing to handle complex, large-scale models.

Conclusion

Mathematical modeling has profoundly advanced our understanding of waterborne disease dynamics, offering invaluable tools for outbreak prediction and intervention planning. Despite challenges, ongoing advancements in data integration and computational methods hold promise for more precise and actionable models. Strengthened interdisciplinary collaboration will be pivotal in addressing future waterborne disease challenges.

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Convection Problems for Certain Hyperbolic PDEs

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Abstract

The "Riemann Problem for Hyperbolic Systems of Partial Differential Equations" poses a significant challenge in computational mathematics and fluid dynamics. This project focuses on investigating and comparing four prominent numerical schemes—Lax-Friedrichs, Lax-Wendroff, Warming-Beam, and Godunov—for solving this complex problem. Each scheme offers distinct advantages and limitations in approximating solutions to hyperbolic systems, motivating a comparative analysis to discern their efficacy across various scenarios. Employing rigorous mathematical formulations and computational simulations, this study delves into the behavior of these schemes under diverse conditions, aiming to elucidate their respective strengths and weaknesses. Through meticulous examination of numerical accuracy, stability, and computational efficiency, this research contributes to a deeper understanding of numerical methods for hyperbolic systems. By synthesizing theoretical insights with computational results, this investigation provides valuable insights into the practical applicability of these schemes, paving the way for informed decision-making in computational fluid dynamics and related fields.

Introduction

The classical advection equation is commonly used as an example of a hyperbolic partial differential equation that demonstrates many characteristics of convection problems.

The Linear Advection Equation

A general, time-dependent linear advection equation in three space dimensions reads

$$u_t + a(x, y, z, t)u_x + b(x, y, z, t)u_y + c(x, y, z, t)u_z = 0 \quad (1)$$

where the unknown is $u = u(x, y, z, t)$ and a, b, c are variable coefficients. If the coefficients are sufficiently smooth one can express above equation as a conservation law with source terms, namely

$$u_t + (au)_x + (bu)_y + (cu)_z = u(a_x + b_y + c_z) \quad (2)$$

In this section we study in detail the initial-value problem (IVP) for the special case of the linear advection equation, namely

$$\left. \begin{array}{l} \text{PDE: } u_t + au_x = 0, -\infty < x < \infty, t > 0 \\ \text{IC: } u(x, 0) = u_0(x), \end{array} \right\} \quad (3)$$

where a is a constant wave propagation speed. The initial data at time $t = 0$ is a function of x alone and is denoted by $u_0(x)$. We warn the reader that for systems we shall use a different notation for the initial data. Generally, we shall not be explicit about the conditions $-\infty < x < \infty; t > 0$ on the independent variables when stating an initial-value problem. The above PDE is the simplest hyperbolic PDE and the simplest hyperbolic conservation law. It is a very useful model equation for the purpose of studying numerical methods for hyperbolic conservation laws, in the same way as the linear, first-order ordinary differential equation

$$\frac{dx}{dt} = \beta, x = x(t), \beta = \text{constant} \quad (4)$$

is a popular model equation for analysing numerical methods for Ordinary Differential Equation (ODEs).

The Riemann Problem

By using geometric arguments, we have constructed the analytical solution of the general IVP (3) for the linear advection equation. Now we study a special IVP called the Riemann problem

$$\left. \begin{array}{l} \text{PDE: } u_t + au_x = 0 \\ \text{IC: } u(x, 0) = u_0(x) = \begin{cases} u_L & \text{if } x < 0, \\ u_R & \text{if } x > 0, \end{cases} \end{array} \right\} \quad (5)$$

where u_L (left) and u_R (right) are two constant values, as shown in Fig. 1. Note that the initial data has a discontinuity at $x = 0$. IVP (5) is the simplest initial-value problem one can pose. The trivial case would result when $u_L = u_R$. From the previous discussion on the solution of the general IVP (3) we expect any point on the initial

profile to propagate a distance $d = at$ in time t . In particular, we expect the initial discontinuity at $x = 0$ to propagate a distance $d = at$ in time t . This particular characteristic curve $x = at$ will then separate those characteristic curves to the left, on which the solution takes on the value u_L , from those curves to the right, on which the solution takes on the value u_R ; see Fig. 2. So, the solution of the Riemann problem (5) is simply

$$u(x, t) = u_0(x - at) = \begin{cases} u_L & \text{if } x - at < 0 \\ u_R & \text{if } x - at > 0 \end{cases} \quad (6)$$

Solution (6) also follows directly from the general solution namely

$$u(x, t) = u_0(x - at). \text{ From (1.25), } u_0(x - at) = u_L \text{ if } x - at < 0 \quad (7)$$

and $u_0(x - at) = u_R$ if $x - at > 0$. The solution of the Riemann problem can be represented in the $x - t$ plane, as shown in Fig. 1. Through any point x_0 on the x -axis one can draw a characteristic. As a constant these are all parallel to each other. For the solution of the Riemann problem the characteristic that passes through $x = 0$ is significant. This is the only one across which the solution changes.

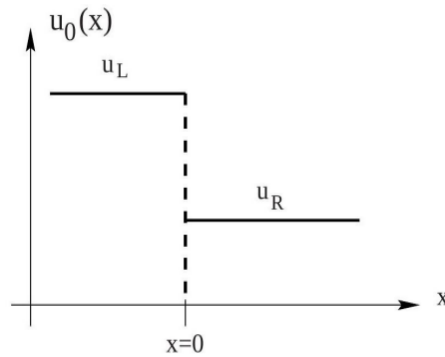


Fig. 1: Illustration of the initial data for the Riemann problem. At the initial time the data consists of two constant states separated by a discontinuity at $x = 0$

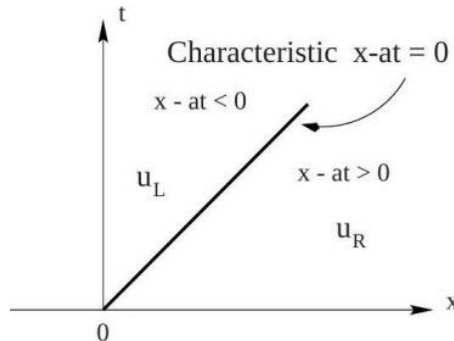


Fig. 2: Illustration of the solution of the Riemann problem in the $x - t$ plane for the linear advection equation with positive characteristic speed a

Numerical Results

We apply four schemes to solve

$$u_t + f(u)_x = 0, f(u) = au, a = \text{constant} \quad (8)$$

with two types of initial conditions.

Test 1 for linear advection (smooth data)

Here the initial condition is the smooth profile

$$u(x, 0) = \alpha e^{-\beta x^2} \quad (9)$$

In the computations we take $a = 1.0, \alpha = 1.0, \beta = 8.0$ and a CFL coefficient $C_{cf} = 0.8$; the initial profile $u(x, 0)$ is evaluated in the interval $-1 \leq x \leq 1$. Computed result is shown in Figs. 3; these correspond respectively to the output times $t = 0.64$ unit and $t = 0.992$. In each figure we compare the exact solution (shown by full lines) with the numerical solution.

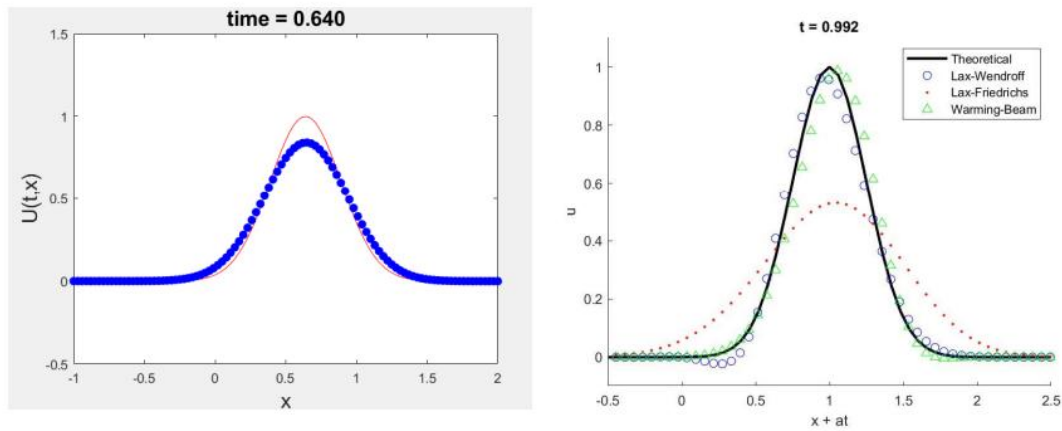


Fig. 3: Plot produced using MATLAB for linear advection equation for smooth data at the given time.

Test 2 for linear advection (discontinuous data)

Now the initial data for equation (8) consists of a square wave, namely

$$u(x, 0) = \begin{cases} 0 & \text{if } x \leq 0.3 \\ 1 & \text{if } 0.3 \leq x \leq 0.7 \\ 0 & \text{if } x \geq 0.7 \end{cases} \quad (10)$$

The computed results for the three output times are shown in Figs. 4. As for Test 1 the effects of numerical diffusion in the first-order methods and the effects of dispersion in the second-order methods lead to visible errors in the numerical solution (symbols), as compared with the exact solution (full line).

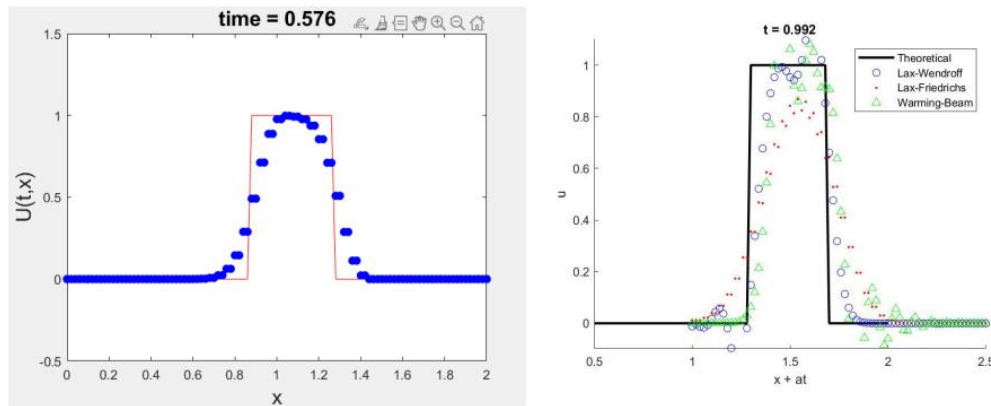
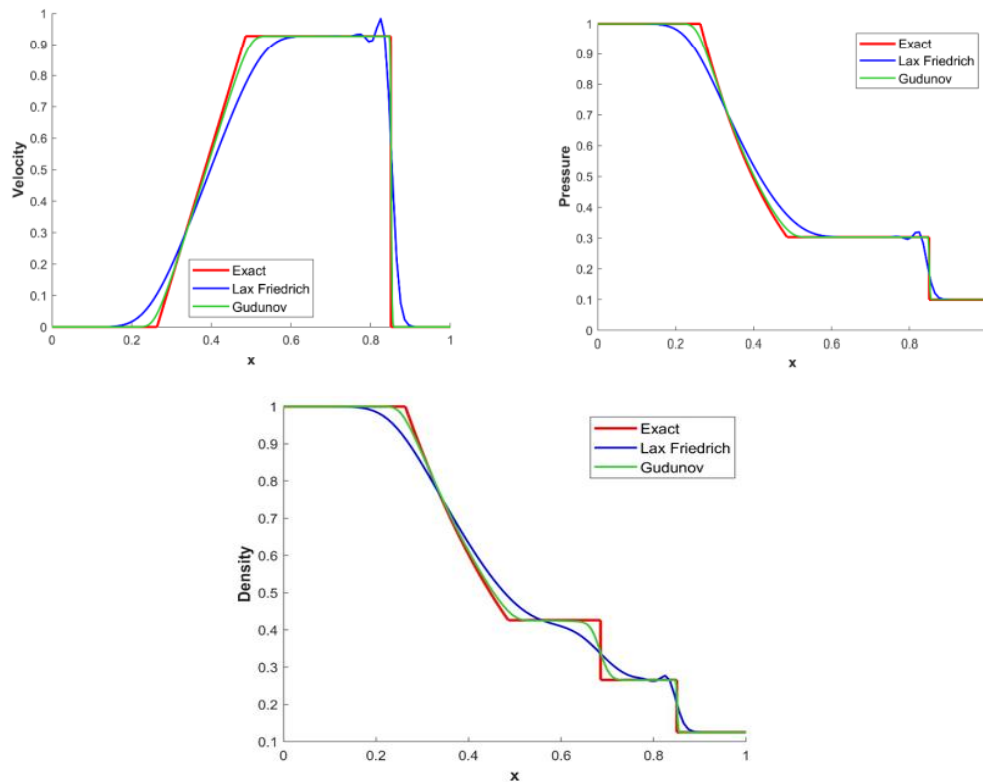


Fig. 4: Plot produced using MATLAB for linear advection equation for discontinuous data at the given time

Numerical Scheme Solutions for Riemann Problem

Performing the Godunov's scheme and Lax-Friedrichs scheme on Test-1 discussed earlier in Chapter 3 which is the so-called Sod test problem; this is a very mild test and its solution consists of a left rarefaction, a contact, and a right shock. Figure below shows solution profiles for density, velocity, pressure, and specific internal energy across the complete wave structure, at time $t = 0.25$ units.



Conclusion

In conclusion, this paper has been an enriching voyage in to the realm of computational fluid dynamics, delving deeply into the intricacies of Riemann problems, shock waves, and rarefactions. Through meticulous study and hands-on implementation, We have garnered a profound understanding of various numerical methodologies, including Godunov's, Lax-Friedrichs, and Lax-Wendroff methods. By employing these techniques in MATLAB, We have gained practical insights into their behaviors, strengths, and limitations when applied to solving the linear advection equation.

Recognizing Riemann problems as fund a mental to grasping wave behaviors, particularly shocks and rarefactions, underscores the criticality of employing accurate numerical approaches to capture these phenomena effectively. Moreover, juxtaposing exact solutions against numerical approximations has underscored the inherent trade-offs between computational efficiency and precision inherent in these methods. In today's era, where computational simulations drive innovations across diverse sectors such as climate modeling and aerospace engineering, the significance of robust numerical methodologies in predicting complex wave behaviors cannot be overstated. The skills and knowledge acquired from this project resonate deeply with the current demand for precise and efficient simulations in our rapidly evolving technological landscape.

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Quantifying Parameter Uncertainty and Robustness of a Non-Linear Nipah Model: A Mathematical Approach

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Abstract

Uncertainty is an inherent feature of mathematical modeling of epidemics and uncertainty influences the reliability of a model. Uncertainty has an effect on computation of solutions of an epidemic system and may grow along with the model evolution. In case of an intricate epidemic model, uncertainties could not be made arbitrarily small and ignored consequently. Uncertainty indwells either in model formulation or in initial conditions. To quantify the robustness of the model parameters, sensitivity analysis is an essential mathematical tool. We proposed a four dimensional ODE compartmental deterministic model depicting Nipah virus transmission. The basic reproduction number (R_0) of the epidemic system is computed. Sensitivity analysis is performed to detect the normalized forward sensitivity indices of the model parameters associated with the basic reproduction number. Numerical simulations are evaluating the feasible strategies to prevent the Nipah transmission.

Keywords: Nipah, Basic Reproduction Number, Sensitivity Analysis.

Introduction

Nipah virus infection (NiV) is an emerging zoonotic infectious disease from animals (bats or pigs) to humans through contact with infected animals or

contaminated body fluids, or via contaminated foods and drinks. Person to person direct contact is less common for Nipah transmission. Nipah virus (NiV) is predominantly found in the urine, saliva, feces, tissue, body fluids of birthing infected fruit bats of *Pteropus* bat species [WHO (1) (2018)]. Nipah (NiV) virus is a member of Paramyxoviridae family, and of Henipavirus genus. The fatality case of Nipah ranges is found to be very high (40% to 75%). First outbreak of Nipah was eventuated in Malaysia and Singapore in the year 1998 and 1999 respectively. Thereafter, Nipah was detected in Bangladesh in the year 2001 and annual outbreaks of Nipah was frequently in Bangladesh as well as in Eastern India till now [CDC (2024)]. The incubation period of Nipah is varying from 4 to 14 days, however 45 days of incubation period also has been reported. Predominant symptoms of Nipah are fever, headache, vomiting, sore throat, muscle pain (myalgia) etc including severe complications like dizziness, drowsiness, respiratory distress, altered consciousness, seizures etc. Since preliminary signs and symptoms of Nipah virus infection are comprehensive, accurate diagnosis could be hindered and challenging in detecting disease prevalence, epidemic outbreak, and its possible effective control measures [WHO (1) (2018)]. In the South-East Asia region, Nipah virus infection be transformed into an intimidating disease due to its high mortality, periodic occurrence, and the unsatisfactory effects of available antivirals. World Health Organization (WHO) R & D announced the Nipah virus (NiV) in WHO's blueprint list in the year 2018 [WHO (2) (2018)]. Until now, any treatment or vaccine is available neither for human beings nor for animals. Only supportive care is recommended to fight against Nipah.

Mathematical models are very beneficent in analyzing the pathological traits of any epidemic outbreak. To investigate the overall transmission dynamics of Nipah, mathematical models would help in perceiving of its possible control and preventive measures; however, a few mathematical models of Nipah are available presently [Barman (2024), Barua (2023), Biswas (2012), Biswas (2014), Das (2020)]. In the mathematical model proposed by Zewdie and Gakkhar [Zewdie (2020)], the authors formulated a SIRD model to investigate the impact of contact with Nipah infected dead bodies and handling them before the burial or cremation process as well as the influence of disposal rate of on the transmission dynamics of Nipah virus infection. In our proposed work, we modified and upgraded the model proposed in [Zewdie (2020)] by incorporating a nonlinear functional response in handling dead bodies. Thereafter, we analyze the sensitivity of the model parameters using normalized forward sensitivity indices method to measure their robustness on overall disease dynamics.

The article is synchronized as follows: in the next Section 2, a mathematical model of Nipah virus transmission dynamics is formulated. In Section 3, the basic qualitative properties of the model are analyzed. Section 3 is dealing with the investigation of steady states and basic reproduction number of the system. In Section 4, sensitivity analysis is performed. Section 5 is demonstrating the biological

interpretation of various numerical simulations. Finally, we discuss and attach some conclusions regarding gained results.

Model Formulation

Investigating the responses of etiological agent (NiV), disease prevalence, disease transmission and transmission procedure of Nipah virus transmission, we have proposed a deterministic mathematical model upgrading the model proposed in [Zewdie (2020)] considering four compartments - (i) $S(t) \rightarrow$ Susceptible, (ii) $I(t) \rightarrow$ Infected, (iii) $R(t) \rightarrow$ Recovered, and (iv) $D(t) \rightarrow$ deceased body compartment representing the number of unburied dead bodies of infected individuals. Our proposed coupled system of ordinary differential equations is as follows:

$$\frac{dS}{dt} = \Lambda - \beta SI + \eta R - \delta S, \frac{dI}{dt} = \beta SI - \theta I - \frac{\mu I}{a+I} - \delta I, \frac{dR}{dt} = \theta I - \eta R - \delta R, \frac{dD}{dt} = \frac{\epsilon \mu I}{a+I} - \gamma D, \quad (1)$$

along with epidemiologically feasible non-negative initial conditions:

$$S(0) = S_0 \geq 0, I(0) = I_0 \geq 0, R(0) = R_0 \geq 0, D(0) = D_0 \geq 0. \quad (2)$$

The time t_0 (day) is indicating the initial day of Nipah infection. The term Λ is representing the constant recruitment rate of susceptible individuals into the epidemic system. The parameter β stands for the disease transmission rate. The term δ stands for the natural death rate of all individuals. The term η is describing the rate of waning of immunity, that is, rate of reinfection. Reinfection of Nipah is a serious concern announced by the World Health Organization. Here, θ stands for the rate of recovery. The parameter μ is describing the disease-induced death rate and ϵ is an adjusting factor. The term γ is representing the disposition rate of dead bodies. All the parameters are positive and their values for numerical simulations are enlisted in Table 1.

Table 1: Descriptions and values of the parameters belong to SIRD model (1)

Parameter	Description	Value	Sources
Λ	constant recruitment of susceptible animals	20	[Zewdie (2020)]
β	disease transmission rate	0.0045	assumed
η	rate of waning of immunity	0.05	[Zewdie (2020)]
δ	natural death rate of individuals	0.02	[Zewdie (2020)]
θ	rate of recovery	0.85	[Mondal (2017)]
μ	disease-induced death rate	0.076	[Zewdie (2020)]
a	half-saturation constant	1	assumed
ϵ	fraction of dead bodies that are not handled safely	[0, 1]	-

Qualitative Properties of the Model

In this Section, the fundamental characteristics of the epidemic system (1) together with initial conditions (2) would be analyzed. To check whether an epidemic system is biologically feasible and well-posed or not, the positivity of the solutions and the uniform boundedness of the system must be investigated.

Positivity

Theorem 1. Every solution of the Nipah virus system of equation system (1) together with non-negative initial conditions (2) defined on is positive, for all $t > 0$.

Proof. The system of equations (1) could be represented in vector form as

$$\dot{Z} = WZ(t), \quad (3)$$

where $Z = \text{col}(S, I, R, D)$, $Z(0) = \text{col}(S(0), I(0), R(0), D(0))$ with

$$\begin{aligned} & \left(W_1(Z(t))W_2(Z(t))W_3(Z(t))W_4(Z(t)) \right) \\ & = \left(\Lambda - \beta SI + \eta R - \delta S\beta SI - \theta I - \frac{\mu I}{a + I} - \delta I\theta I - \eta R - \delta R \frac{\epsilon \mu I}{a + I} - \gamma D \right), \end{aligned}$$

with $W: \mathbb{R}^4 \rightarrow \mathbb{R}_+^4$ and $W \in C^\infty(\mathbb{R}^4)$. It is obvious that in the Nipah virus system of equation (1), $W_i(Z_i)|_{Z_i} \geq 0$, for $i = 1, 2, 3, 4$. According to Nagumo's Theorem [3], we conclude that the solution of (3) together with initial conditions $W_0 \in \mathbb{R}_+^4$, say $W(t) = W(t, W_0)$ such that $W \in \mathbb{R}_+^4$ for all finite time. Hence the proof.

Boundedness

Theorem 2. Every solution of the Nipah virus system of equation (1) together with non-negative initial conditions (2) in \mathbb{R}_+^4 are uniformly bounded.

Proof. Summing up all the four equations of the Nipah virus model system (1), we get

$$\frac{dN}{dt} = \Lambda - \delta(S + I + R) - \gamma D \Rightarrow \frac{dN}{dt} + \zeta N = \Lambda,$$

where $\zeta = \min\{\delta, \gamma\}$. Now, integrating both side of the above equation we obtain

$$0 < N(S, I, R, D) \leq \frac{\Lambda}{\zeta} + N(0)e^{-\zeta t},$$

where, $N(0) = S(0) + I(0) + R(0) + D(0)$. When $t \rightarrow +\infty$, we can get $0 < N \leq \frac{\Lambda}{\zeta}$

Consequently, it could be concluded that all the solutions of the Nipah virus model system (1) initiating in the region $\{\mathbb{R}_+^4 \setminus 0\}$ are positively invariant and uniformly bounded in the region Ω defined as

$$\Omega = \{ (S, I, R, D) \in \mathbb{R}_+^4 : 0 < S + I + R + D \leq \frac{\Lambda}{\zeta} \}.$$

Hence the proof.

Steady States and basic Reproduction Number of the System

In this Section, we investigate the biologically feasible steady states executed by the Nipah epidemic system (1) and the basic reproduction number (R_0) of the system which play crucial role in Nipah transmission dynamics.

Equilibrium Points

The Nipha virus epidemic system (1) possesses two biologically feasible steady states:

- The Nipha virus-free equilibrium (NVEF) $\Pi_0 = \left(\frac{\Lambda}{\delta}, 0, 0, 0\right)$ is always existent irrespective of any epidemic condition;
- The Nipha virus existing equilibrium (NVEE) $\Pi^* = (S^*, I^*, R^*, D^*)$, whose existence conditions would be studied further.

Basic Reproduction Number

Basic reproduction number plays the central role in studying disease prevalence, disease transmission, disease progression and overall intricate transmission dynamics. It is the average number of secondary infections in a whole susceptible population initiated from primary infections. Using the Next-generation matrix method [8, 10], the basic reproduction number of the Nipah epidemic system (1) is computed as

$$R_0 = \frac{\Lambda a \beta}{\delta[a(\theta + \delta) + \mu]}.$$

Existence of NVEE

The components of the Nipah virus existing equilibrium (NVEE) $\Pi^* = (S^*, I^*, R^*, D^*)$ are computed as

$$S^* = \frac{1}{\beta} \left[\theta + \delta + \frac{\mu}{a + I^*} \right], \quad R^* = \frac{\theta}{\eta + \delta} I^*, \quad D^* = \frac{\epsilon \mu}{\gamma(a + I^*)} I^*,$$

and I^* is a positive root of the following quadratic equation:

$$\kappa_1 I^{*2} + \kappa_2 I^* + \kappa_3 = 0, \quad (4)$$

where $\kappa_1 = \delta(\eta + \theta + \delta)$,

$$\kappa_2 = [(\theta + \delta)(\beta a + \delta) + \mu \beta](\eta + \delta) - [\Lambda(\eta + \delta) + \eta \theta a] \beta,$$

$$\kappa_3 = \delta[(\theta + \delta) + \mu](\eta + \delta)(1 - R_0).$$

From the above quadratic equation (4), it is clear that the equation executes unique root if and only if (i). $\frac{[(\theta + \delta)(\beta a + \delta) + \mu \beta](\eta + \delta)}{[\Lambda(\eta + \delta) + \eta \theta a] \beta} > 1$, and (ii). $R_0 > 1$. Therefore, the Nipah virus existing equilibrium (NVEE) $\Pi^* = (S^*, I^*, R^*, D^*)$ for the system (1) have unique positive root if and only if $R_0 > 1$ and $\frac{[(\theta + \delta)(\beta a + \delta) + \mu \beta](\eta + \delta)}{[\Lambda(\eta + \delta) + \eta \theta a] \beta} > 1$.

Sensitivity Analysis

In this Section, sensitivity analysis is performed to measure the impact of the model parameters in disease prevalence and transmission, mortality as well as in disease eradication [10]. With the help of normalized forward sensitivity index method, we calculate the normalized sensitivity indices of R_0 corresponding to each baseline parameter associated to the explicit expression of R_0 . With respect to the rate of transmissibility of infection (β) is given by $\Pi_{\beta}^{R_0} = \frac{\partial R_0}{\partial \beta} \times \frac{\beta}{R_0}$. For example, $\Pi_{\beta}^{R_0} = 1$ and this sensitivity index implies that increasing β by 10% will increase by 10%. Consequently, it could be concluded that in controlling the Nipah (NiV) infection, the rate of transmission of Nipah infection (β) must be reduced.

Applying the following normalized forward sensitivity formula,

$$\Sigma_{c_i}^{R_0} = \frac{\partial R_0}{\partial c_i} \times \frac{c_i}{R_0},$$

where c_i are the parameters associated to the basic reproduction number R_0 , we compute sensitivity analysis of each parameter associated to the basic reproduction number of the model.

$$\begin{aligned}\Sigma_{\Lambda}^{R_0} &= \frac{\partial R_0}{\partial \Lambda} \times \frac{\Lambda}{R_0} = 1 > 0, \\ \Sigma_{\beta}^{R_0} &= \frac{\partial R_0}{\partial \beta} \times \frac{\beta}{R_0} = 1 > 0, \\ \Sigma_a^{R_0} &= \frac{\partial R_0}{\partial a} \times \frac{a}{R_0} = \frac{\mu}{a(\theta + \delta) + \mu} > 0, \\ \Sigma_{\mu}^{R_0} &= \frac{\partial R_0}{\partial \mu} \times \frac{\mu}{R_0} = -\frac{\mu}{a(\theta + \delta) + \mu} < 0, \\ \Sigma_{\theta}^{R_0} &= \frac{\partial R_0}{\partial \theta} \times \frac{\theta}{R_0} = -\frac{a\theta}{a(\theta + \delta) + \mu} < 0, \\ \Sigma_{\delta}^{R_0} &= \frac{\partial R_0}{\partial \delta} \times \frac{\delta}{R_0} = -\frac{\mu + a(\theta + 2\delta)}{a(\theta + \delta) + \mu} < 0,\end{aligned}$$

Table 2: Sensitivity indices of model parameters associated to the basic reproduction number, R_0 of the Nipah epidemic system (1).

Parameters	Λ	θ	β	μ	a	δ
Sensitivity indices	1.0000	-0.9081	1.0000	-0.0705	0.0750	-0.9957

From the Table 2, it is observed that for the Nipah epidemic system (1), the most sensitive parameters are the constant recruitment of susceptible animals (Λ), rate of transmission of Nipah infection (β), natural death rate of individuals (δ) and rate of recovery from Nipah (θ). We should pay more attention to these most influential parameters to yield proper intervention strategies in controlling the Nipah virus

transmission. The least influencing parameters are disease-induced death rate (μ) and half-saturation constant (a). We may pay less attention to these parameters in overall transmission process. The most influential parameters which have positive correlation with the basic reproduction number are Λ and β implying the fact that increasing the value of these parameters will increase the value of R_0 . On the other hand, the most influential parameters which have negative correlation with the basic reproduction number are θ and δ implying the fact that decreasing the value of these parameters will increase the value of R_0 . The tornado plot of the sensitivity indices is portrayed in the Figure 1.

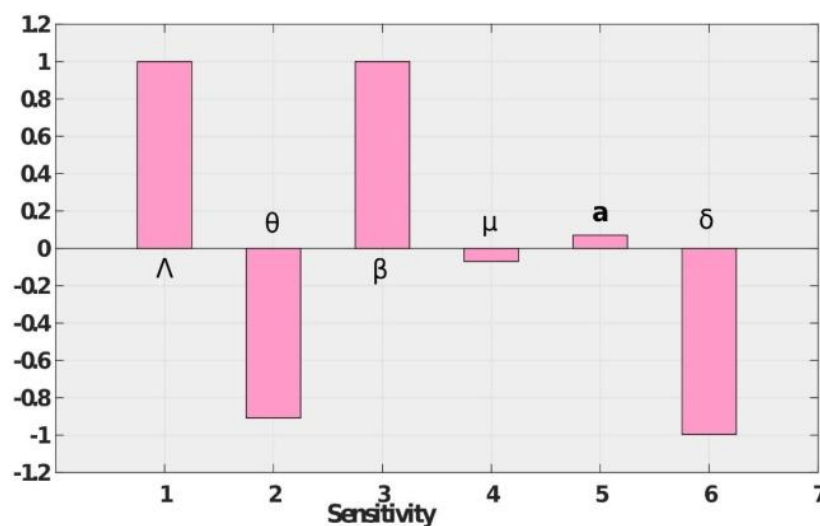


Fig. 1: Figure represents tornado plot of the sensitivity indices of the model parameters associated to the basic reproduction number, R_0 of the Nipah epidemic system (1)

Discussion and Conclusion

Calibrating the dynamical attributes of Nipah transmission, a four dimensional deterministic compartmental model is formulated. The positivity and boundedness of the solutions of the Nipah epidemic system are analyzed. The steady states possessed by the Nipah epidemic system (1) are investigated and it is seen that the system (1) executes two equilibrium points - one is Nipah virus free equilibrium point and another is Nipah virus existing equilibrium. The basic reproduction number (R_0) of the system (1) is computed. The sensitivity analysis of the model parameters are analyzed using the normalized forward sensitivity method. It is found that the most sensitive parameters are the constant recruitment of susceptible animals (Λ), rate of transmission of Nipah infection (β), natural death rate of individuals (δ) and rate of recovery from Nipah (θ). Tornado plot of sensitivity analysis is showing that we need to pay more attentions to these parameters in eradicating and curtailing the chain of

Nipah virus transmission and reinfection of Nipah. More researches should be conducted on controlling the reinfection of Nipah virus transmission so that the global burden of the Nipah would be diminished worldwide.

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Statistical Convergence to Convergence in Statistics: A Journey

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Abstract

Statistical convergence was introduced in connection with problems of series summation. The main idea of the statistical convergence of a sequence I is that the majority of elements from I converge and we do not care what is going on with other elements. We show (Section 2) that being mathematically formalized the concept of statistical convergence is directly connected to convergence of such statistical characteristics as the mean and standard deviation. At the same time, it is known that sequences that come from real life sources, such as measurement and computation, do not allow, in a general case, to test whether they converge or statistically converge in the strict mathematical sense. To overcome limitations induced by vagueness and uncertainty of real life data, neoclassical analysis has been developed. It extends the scope and results of the classical mathematical analysis by applying fuzzy logic to conventional mathematical objects, such as functions, sequences, and series. The goal of this work is the further development of neoclassical analysis. This allows us to reflect and model vagueness and uncertainty of our knowledge, which results from imprecision of measurement and inaccuracy of computation. In the context of the theory of fuzzy limits, we develop the structure of statistical fuzzy convergence and study its properties. Relations between statistical fuzzy convergence and fuzzy convergence are considered in Theorems 3.1 and 3.2. Algebraic structures of statistical fuzzy limits are described in Theorem 3.5. Topological structures of statistical fuzzy limits are described in Theorems 3.3 and 3.4. Relations between statistical fuzzy convergence and fuzzy convergence of statistical characteristics, such

as the mean (average) and standard deviation, are studied in Section 4. Introduced constructions and obtained results open new directions for further research that are considered in the Conclusion.

Keywords: Statistical Convergence, Mean, Standard Deviation, Fuzzy Limit, Statistics, Fuzzy Converge.

Introduction

The idea of statistical convergence goes back to the first edition (published in Warsaw in 1935) of the monograph of Zygmund [37]. Formally the concept of statistical convergence was introduced by Steinhaus [34] and Fast [18] and later reintroduced by Schoenberg [33].

Statistical convergence, while introduced over nearly fifty years ago, has only recently become an area of active research. Different mathematicians studied properties of statistical convergence and applied this concept in various areas such as measure theory [30], trigonometric series [37], approximation theory [16], locally convex spaces [29], finitely additive set functions [14], in the study of subsets of the Stone-Chech compactification of the set of natural numbers [13], and Banach spaces [15].

However, in a general case, neither limits nor statistical limits can be calculated or measured with absolute precision. To reflect this imprecision and to model it by mathematical structures, several approaches in mathematics have been developed: fuzzy set theory, fuzzy logic, interval analysis, set valued analysis, etc. One of these approaches is the neoclassical analysis (cf., for example, [7, 8]). In it, ordinary structures of analysis, that is, functions, sequences, series, and operators, are studied by means of fuzzy concepts: fuzzy limits, fuzzy continuity, and fuzzy derivatives. For example, continuous functions, which are studied in the classical analysis, become a part of the set of the fuzzy continuous functions studied in neoclassical analysis. Neoclassical analysis extends methods of classical calculus to reflect uncertainties that arise in computations and measurements.

The aim of the present paper is to extend and study the concept of statistical convergence utilizing a fuzzy logic approach and principles of the neoclassical analysis, which is a new branch of fuzzy mathematics and extends possibilities provided by the classical analysis [7, 8]. Ideas of fuzzy logic have been used not only in many applications, such as, in bifurcation of non-linear dynamical systems, in the control of chaos, in the computer programming, in the quantum physics, but also in various Statistical Convergence and Convergence in Statistics 3 branches of

mathematics, such as, theory of metric and topological spaces, studies of convergence of sequences and functions, in the theory of linear systems, etc.

In the second section of this paper, going after introduction, we remind basic constructions from the theory of statistical convergence consider relations between statistical convergence, ergodic systems, and convergence of statistical characteristics such as the mean (average), and standard deviation. In the third section, we introduce a new type of fuzzy convergence, the concept of statistical fuzzy convergence, and give a useful characterization of this type of convergence. In the fourth section, we consider relations between statistical fuzzy convergence and fuzzy convergence of statistical characteristics such as the mean (average) and standard deviation

For simplicity, we consider here only sequences of real numbers. However, in a similar way, it is possible to define statistical fuzzy convergence for sequences of complex numbers and obtain similar properties.

Convergence in Statistics

Statistics is concerned with the collection and analysis of data and with making estimations and predictions from the data. Typically two branches of statistics are discerned: descriptive and inferential. Inferential statistics is usually used for two tasks: to estimate properties of a population given sample characteristics and to predict properties of a system given its past and current properties. To do this, specific statistical constructions were invented. The most popular and useful of them are the average or mean (or more exactly, arithmetic mean) μ and standard deviation σ (variance σ^2).

To make predictions for future, statistics accumulates data for some period of time. To know about the whole population, samples are used. Normally such inferences (for future or for population) are based on some assumptions on limit processes and their convergence. Iterative processes are used widely in statistics. For instance the empirical approach to probability is based on the law (or better to say, conjecture) of big numbers, 4 Mark Burgin and Oktay Duman states that a procedure repeated again and again, the relative frequency probability tends to approach the actual probability. The foundation for estimating population parameters and hypothesis testing is formed by the central limit theorem, which tells us how sample means change when the sample size grows. In experiments, scientists measure how statistical characteristics (e.g., means or standard deviations) converge (cf., for example, [23, 31]).

Convergence of means/averages and standard deviations has been studied by many authors and applied to different problems (cf. [1-4, 17, 19, 20, 24-28, 35]). Convergence of statistical characteristics such as the average/mean and standard

deviation are related to statistical convergence as we show in this section and Section 4.

Consider a subset K of the set N of all natural numbers. Then $K_n = \{k \in K; k \leq n\}$.

Definition: The asymptotic density $d(K)$ of the set K is equal to

$$\lim_{n \rightarrow \infty} \left(\frac{1}{n} \right) |K_n|$$

whenever the limit exists; here $|B|$ denotes the cardinality of the set B .

Let us consider a sequence $\{a_i; i = 1, 2, 3, \dots\}$ of real numbers, real number a , and the set

$$L_{\epsilon(a)} = \{i \in N : |a_i - a| \geq \epsilon\}$$

Definition: The asymptotic density, or simply, density $d(I)$ of the sequence I with respect to a and ϵ is equal to $d(L_{\epsilon}(a))$.

Asymptotic density allows us to define statistical convergence

Definition 2.3: A sequence $I = \{a_i; i = 1, 2, 3, \dots\}$ is statistically convergent to a if $d(L_{\epsilon}(a)) = 0$ for every $\epsilon > 0$. The number (point a) is called the statistical limit of I . We denote this by $a = \text{stat-lim } I$.

Statistical Convergence and Convergence in Statistics

Note that convergent sequences are statistically convergent since all finite subsets of the natural numbers have density zero. However, its converse is not true [21, 33]. This is also demonstrated by the following example.

Let us consider the sequence $I = \{a_i; i = 1, 2, 3, \dots\}$ whose terms are

$$a_i = \begin{cases} i & \text{when } i = n^2 \text{ for all } n = 1, 2, 3, \dots \\ 1/i & \text{Otherwise} \end{cases}$$

see that the sequence I is divergent in the ordinary sense, while 0 is the statistical limit of I since $d(K) = 0$ where $K = \{n^2 \text{ for all } n = 1, 2, 3, \dots\}$. Not all properties of convergent sequences are true for statistical convergence. For instance, it is known that a subsequence of a convergent sequence is convergent. However, for statistical convergence this is not true. Indeed, the sequence $h = \{i; i = 1, 2, 3, \dots\}$ is a subsequence of the statistically convergent sequence I from Example 2.1. At the same time, h is statistically divergent. However, if we consider dense sub-sequences of fuzzy convergent sequences, it is possible to prove the corresponding result

Definition: A subset K of the set N is called statistically dense if $d(K) = 1$.

Example: The set $\{i \neq n^2; i = 1, 2, 3, \dots; n = 1, 2, 3, \dots\}$ is statistically dense, while the set $\{3i; i = 1, 2, 3, \dots\}$ is not.

Note: A statistically dense subset of a statistically dense set is a statistically dense set. The intersection and union of two statistically dense sets are statistically dense sets.

Definition: A subsequence h of the sequence l is called statistically dense in l if the set of all indices of elements from h is statistically dense.

A statistically dense subsequence of a statistically dense subsequence of l is a statistically dense subsequence of l . The intersection and union of two statistically dense subsequences are statistically dense sub-sequences.

Theorem: A sequence l is statistically convergent if and only if any statistically dense subsequence of l is statistically convergent **Proof.** Necessity-Let us take a statistically convergent sequence $l = \{a_i; i = 1, 2, 3, \dots\}$ and a statistically dense subsequence $h = \{b_k; k = 1, 2, 3, \dots\}$ of l . Let us also assume that h statistically diverges. Then for any real number a , there is some $\varepsilon > 0$ such that $\liminf_{n \rightarrow \infty} \left(\frac{1}{n}\right) |H_n, \varepsilon(a)| = d > 0$ for some

$$d \in (0, 1), H_n, \varepsilon(a) = \{k \leq n; |b_k - a| > \varepsilon\}$$

ε . As h is a l , we have $L_{n, \varepsilon}(a) \supset H_n, \varepsilon(a)$ where $L_{n, \varepsilon}(a) = \{i \leq n; |a_i - a| > \varepsilon\}$

Consequently, $\liminf_{n \rightarrow \infty} \left(\frac{1}{n}\right) |L_n, \varepsilon(a)| \geq d > 0$, which yields that $d(\{i; |a_i - a| > \varepsilon\}) \neq 0$. Thus l is also statistically divergent.

Sufficiency follows from the fact that l is a statistically dense subsequence of itself.

A statistically dense subsequence of a statistically convergent sequence is statistically convergent. To each sequence $l = \{a_i; i = 1, 2, 3, \dots\}$ of real numbers, it is possible to correspond a new sequence

$$\mu(l) = \{\mu_n = \sum_{i=1}^n a_i; n = 1, 2, 3, \dots\}$$

of its partial averages (means). Here a partial average of l is equal to

$$\mu_n = \left(\frac{1}{n}\right) \sum_{i=1}^n a_i.$$

Sequence of a partial average / means play an important role in the theory of ergodic system [5]. Indeed the definition of an ergodic system is based on the concept of the "time average" of the values of some appropriate function g argument for which are dynamic transformation T of a point x from the manifold of the dynamical system. This average is given by the formula

$$g(x) = \left(\frac{1}{n}\right) \sum_{k=1}^{n-1} g(T^k x).$$

In other words, the dynamic average is the limit of the partial average/means of the sequence $\{T^k x; k = 1, 2, 3, \dots\}$.

Let $l = \{a_i; i = 1, 2, 3, \dots\}$ be a bounded sequence, i.e., there is a number m such that $|a_i| < m$ for all $i \in \mathbb{N}$. This condition is usually true for all sequences generated by measurements or computations, i.e., for all sequences of data that come from real life.

Theorem: $a = \text{star} - \lim l$, then $a = \lim_{\mu}(l)$

Proof . Since $a = \text{star} - \lim l$, for every $\varepsilon > 0$, we have

As $|a_i| < m$ for all $i \in N$, there is a number k such that $|a_i - a| < k$ for all $i \in N$. Namely, $|a_i - a| \leq |a_i| + |a| \leq m + |a| = k$. Taking the set $L_{n,\varepsilon}(a) = \{i \leq n, i \in N; |a_i - a| \geq \varepsilon\}$, denoting $|L_{n,\varepsilon}(a)|$ by u_n , and using the hypothesis $|a_i| < m$ for all $i \in N$, we have the following system of inequalities:

$$\begin{aligned} |\mu_n - a| &= \left| \left(\frac{1}{n} \right) \sum_{i=1}^n |a_i - a| \right| \\ &\leq \left(\frac{1}{n} \right) (ku_n + n\varepsilon) \\ &= \varepsilon + k \left(\frac{u_n}{n} \right). \end{aligned}$$

From the equality (2.1), we get, for sufficiently large n , the inequality $|\mu_n - a| < \varepsilon + k\varepsilon$.

Thus, $a = \lim_{\mu}(l)$.

Theorem is proved.

Remark: However, convergence of the partial average /means of sequence does not imply statistical convergence of this sequence as the following example demonstrates.

Example: Let us consider the sequence $l = a_i; i = 1, 2, 3, \dots$ where terms are $a_i = (-1)^i \sqrt{i}$. The sequence is statistically divergent although $\lim_{\mu}(l) = 0$.

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Dynamical System Analysis of Hamiltonian System of Equations

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Abstract

Our work deals with the dynamical system analysis of Hamiltonian system of equations. A dynamical system analysis has been applied to determine the critical points of the autonomous system corresponding to the Hamiltonian system of equations and discussed stability analysis by using Hartman-Grobman theorem. Then we have discussed the stability analysis of the Hamiltonian for an undamped harmonic oscillator by using Hartman-Grobman theorem and Lyapunov stability criterion. Finally, we conclude that both of the method exhibits same type of stability of the system.

Keywords: Hamiltonian System, Nonlinear Dynamics, Hartman-Grobman Theorem, Lyapunov Function.

Introduction

A Hamiltonian system is a dynamical system governed by Hamilton's equations. In physics, this dynamical system describes the evolution of a physical system such as an electron in an electromagnetic field or a planetary system. These systems can be studied in both Hamiltonian mechanics and dynamical systems theory. Hamiltonian systems are linear or nonlinear systems with particular symmetry that allows the stability of equilibrium points to be found and the solution curves to be drawn even though actual solutions are not obtained. Formally, a Hamiltonian system

is a dynamical system characterized by the scalar function $H(p, q, t)$, also known as the Hamiltonian. The state of the system, r , is described by the generalized coordinates p and q , corresponding to generalized momentum and position respectively. Both p and q are real-valued vectors with the same dimension N . Thus, the state is completely described by the $2N$ -dimensional vector $r = (p, q)$ and the evolution equations are given by Hamilton's equations:

$$\frac{dq}{dt} = + \frac{\partial H}{\partial p} \quad (1)$$

$$\frac{dp}{dt} = - \frac{\partial H}{\partial q}. \quad (2)$$

By continuity, the higher order partial derivatives of $H(p, q)$ can be taken in any order so that

$$\frac{\partial^2 H}{\partial q \partial p} = \frac{\partial^2 H}{\partial p \partial q}.$$

In terms of variables of the system, we can write

$$\frac{\partial}{\partial q} \left(\frac{dq}{dt} \right) = - \frac{\partial}{\partial p} \left(\frac{dp}{dt} \right).$$

The entirety of our work is swotted as follows:

In section 2, we determined the critical points corresponding to the autonomous system [(1)-(2)] and discussed stability analysis by using Hartman-Grobman theorem [1,2,3,4]. In section 3, we have discussed the stability analysis of the Hamiltonian for an undamped harmonic oscillator by using Hartman-Grobman theorem [1] and Lyapunov stability criterion [1]. Finally, the brief discussion and concluding remarks of the present work are proposed in section 4.

Critical Points and Stability Analysis

Considering $q = x$ and $p = y$ and then the autonomous system [(1)-(2)] can be rewritten as

$$\frac{dx}{dt} = + \frac{\partial H}{\partial y} = f(x, y) \quad (3)$$

$$\frac{dy}{dt} = - \frac{\partial H}{\partial x} = g(x, y) \quad (4)$$

$$\text{where } f(x, y) = \frac{\partial H}{\partial y} \text{ and } g(x, y) = - \frac{\partial H}{\partial x}.$$

Critical points are values (x_0, y_0) at which the partial derivatives of H vanish,

$$\frac{\partial H}{\partial x}(x_0, y_0) = \frac{\partial H}{\partial y}(x_0, y_0) = 0.$$

Since these are the same as the points at which the system derivatives are also zero, they are equilibrium points of the system

$$(x_0, y_0) = (x_{eq}, y_{eq}).$$

For the Hamiltonian system the Jacobian matrix can be written as

$$J(x, y) = \begin{bmatrix} \frac{\partial f}{\partial x} & \frac{\partial f}{\partial y} & \frac{\partial g}{\partial x} & \frac{\partial g}{\partial y} \\ \frac{\partial^2 H}{\partial x \partial y} & \frac{\partial^2 H}{\partial x^2} & -\frac{\partial^2 H}{\partial y^2} & -\frac{\partial^2 H}{\partial x \partial y} \end{bmatrix}.$$

Considering $\frac{\partial^2 H}{\partial x \partial y} = \alpha$, $\frac{\partial^2 H}{\partial x^2} = \beta$, and $-\frac{\partial^2 H}{\partial y^2} = \gamma$, the trace of the Jacobian matrix is zero and the determinant is

$$D = -\alpha^2 - \beta\gamma.$$

The eigenvalues are solutions of the characteristic equation and those are can be written as

$$\lambda_{1,2} = \frac{T}{2} \pm \frac{\sqrt{T^2 - 4D}}{2} = \pm \sqrt{\alpha^2 + \beta\gamma}.$$

There are limited choices for eigenvalues and phase portraits.

- **Case I:** For $\alpha^2 + \beta\gamma > 0$, the roots are distinct real numbers. They are opposite signs of each other and hence by Hartman-Grobman theorem, we can conclude that the equilibrium point is a saddle node [2,3,4], i.e. unstable in nature.
- **Case II:** For $\alpha^2 + \beta\gamma < 0$, the eigenvalues are purely imaginary and the equilibrium point is a center [1] in the linearized system. In nonhamiltonian systems, the center may be a center or a spiral in the nonlinear system. For the Hamiltonian system, the Hamiltonian is constant along the solution curves, so that Hamiltonian system cannot contain sources or sink, or spiral source or sinks, so it is a center [4,5,6,7].

Stability Discussion of the Hamiltonian for an Undamped Harmonic Oscillator

The Hamiltonian for the undamped harmonic oscillator is

$$H(x, y) = \frac{1}{2}(y^2 + qx^2) \quad (5)$$

where q is a constant. The Hamiltonian system can be written as

$$\frac{dx}{dt} = \frac{\partial H}{\partial y} = y \quad (6)$$

$$\frac{dy}{dt} = -\frac{\partial H}{\partial x} = -qx. \quad (7)$$

The Jacobian matrix corresponding to the above system is

$$J = \begin{bmatrix} 0 & 1 \\ -q & 0 \end{bmatrix}.$$

The characteristic equation of the Jacobian matrix J is given by

$$|J - \lambda I| = 0,$$

$$|-\lambda 1 - q - \lambda| = 0,$$

$$\lambda^2 + q = 0,$$

$$\lambda = \pm\sqrt{-q}.$$

Here we consider three cases, $q > 0$, $q < 0$ and $q = 0$.

Case I: ($q > 0$)

In this case, we have two complex conjugate eigenvalues with zero real parts so the critical point (0,0) behaves as a center (Fig. 1(a)). Thus the critical point (0,0) is stable but not asymptotically.

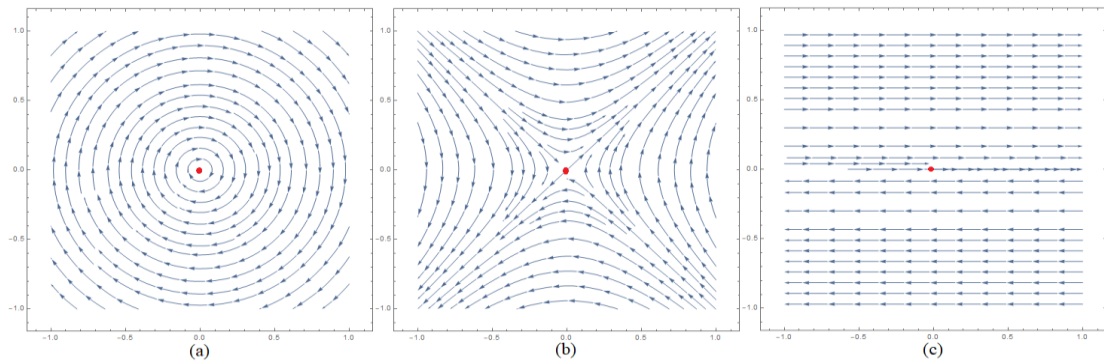


Fig. 1 Profile of the global analysis in finite phase space for several values of q . The horizontal axis represents variable 'x' and the vertical axis represents variable 'y'. Figure (a) corresponds to $q > 0$, (b) corresponds to $q < 0$, and (c) corresponds to $q = 0$

Case II: ($q < 0$)

In this case, we get two real eigenvalues with opposite signs. It follows that the critical point (0,0) behaves as a saddle node (Fig. 1(b)) and unstable in nature.

Case III: ($q = 0$)

In this case, both of the eigenvalues of the Jacobian matrix are 0. By Hartman-Grobman theorem, we cannot conclude about the stability of the critical point. That's why we plotted the phase portrait numerically (Fig. 1(c)) and from the plot, we conclude that the critical point (0,0) is unstable in nature.

Now let's discuss the stability of the Hamiltonian for the undamped harmonic oscillator by using suitable Lyapunov function. To start the discussion, first we state the Lyapunov stability theorem [1].

- **Theorem:** Let E be an open subset of \mathbb{R}^n containing X_0 . Suppose that $f \in C^1(E)$ and that $f(X_0) = 0$. Suppose further that there exists a real valued function $V \in C^1(E)$ satisfying $V(X_0) = 0$ and $V(X) > 0$ if $X \neq X_0$. Then

- if $\dot{V}(X) \leq 0$ for all $X \in E$, X_0 is stable;
- if $\dot{V}(X) < 0$ for all $X \in E \sim X_0$, X_0 is asymptotically stable;
- if $\dot{V}(X) > 0$ for all $X \in E$, X_0 is unstable.

For the previous example, if we consider $V(x,y)$ as the Hamiltonian of the system, i.e.

$$V(x,y) = H(x,y) = \frac{1}{2}(y^2 + qx^2).$$

We see that for $q > 0$,

- $V(x,y) > 0$ for $(x,y) \neq (0,0)$,
- $V(x,y) = 0$ for $(x,y) = (0,0)$,
- $\dot{V}(x,y) = y\dot{y} + qx\dot{x}$
 $= y(-qx) + qx(y)$
 $= 0.$

Thus, we can conclude that $V(x,y) = \frac{1}{2}(y^2 + qx^2) = H(x,y)$ is a Lyapunov function (for $q > 0$) and the origin is stable (not asymptotically) for $q > 0$.

We see that the stability criteria for $q > 0$ is same for Hartman-Grobman theorem as well as Lyapunov stability theorem.

Conclusion

Every physical system possesses its evolution equations in the form of differential equations. Inferring about the properties of the physical system solution of the evolution equations is very much essential. In the context of cosmology, the differential equations are highly coupled and nonlinear in nature and it is almost impossible to have exact solutions. To resolve this issue, the mathematical technique known as dynamical system analysis is very useful as without attempting for exact solutions it is possible to infer about the properties of the model. This work is an example of this dynamical system analysis applied to the general two dimensional Hamiltonian system of equations.

From Case I and Case II of Section 2, we conclude that for a two dimensional Hamiltonian $H(x,y)$ of a physical system, if $\left(\frac{\partial^2 H}{\partial x \partial y}\right)^2 - \frac{\partial^2 H}{\partial x^2} \frac{\partial^2 H}{\partial y^2} > 0$ then the vector field diverges from the equilibrium points due to the saddle node behavior and the system behaves as a center while $\left(\frac{\partial^2 H}{\partial x \partial y}\right)^2 - \frac{\partial^2 H}{\partial x^2} \frac{\partial^2 H}{\partial y^2} < 0$. It is also to be noted that the Hamiltonian system of a physical system can never be shown sources, sink, or spiral source or spiral sink types stability behavior. Next we have discussed the stability analysis of the Hamiltonian (5) for the undamped harmonic oscillator in the perspective of Hartman-Grobman Theorem as well as Lyapunov stability Theorem and we conclude that both of the method exhibit same type of stability of the system for $q > 0$.

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Study of Dengue Model with Temperature Effects under Interval Uncertainty

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Abstract

In this article, we have considered a dengue model with temperature effects under interval uncertainty. This study looked at the temperature-dependent entomological factors of *Aedes aegypti* that contribute to the transmission dynamics of dengue disease in subtropical Taiwan. This study demonstrated the limited pre-adult mosquito maturation rate by demonstrating a positive correlation between the entomological parameter estimations and a progressive temperature increase, but not with the rate of mosquito mortality or maturation. The temperature climatic component had a significant impact on the dynamic modeling of the vector-host interaction, as indicated by the results. Our simulation's results also indicate that temperatures around 32°C are the most conducive to dengue transmission. These findings may be applied to cost-effectiveness analyses and control measure modeling in the future.

Keywords: Dengue Fever, Temperature, Stability Analysis, Numerical Simulation.

Introduction

The parameters of this epidemic model are established by utilising demographic information from the Kaohsiung, Taiwan neighbourhood known as FongShan. Between 1998 and 2010, Kaohsiung, the second-largest city in Taiwan, was particularly vulnerable to dengue epidemics. Between 2001 and 2003, 4,790 cases of dengue fever were reported in Taiwan, making it the country's worst outbreak in 60 years. More than 238,333 cases of dengue have been reported to the WHO recently. Only nations in the Western Pacific Region, which includes Taiwan, will get dengue condition reports after October 2020. Today, epidemiology, computational biology, public health, and environmental sciences have made understanding the effect of temperature on dengue virus disease transmission a major priority due to the serious environmental challenges posed by global warming (see [1–8] and references therein). A new review study [9] uses a meta-analysis to investigate the relationship between precipitation, ambient temperature, and dengue disease. Further research is cited in [11], and deterministic (integer-order) mathematical models for dengue transmission are covered in detail in [10]. These basic vector-host dynamic models involve susceptible-infectious-recovery (SIR) human populations and susceptible-exposed-infectious (SEI) mosquito populations.

A large portion of research on biological mathematical models focuses on deterministic models, which are primarily based on the law of large numbers. These models assume that the system's behavior will display relatively stable statistical patterns when enough biological individuals are considered. To address uncertainties, several researchers have previously used stochastic and interval approaches [12–17]. In the interval method, functions with interval values are used to describe unknown parameters. Most mathematical modeling, especially in bio-mathematics, is done in a precise and clear setting. However, under these conditions, most of the parameters in biological models are inaccurate. Incorporating uncertain factors can make a biological model unreliable.

Pre-requisite Concept

Definition. For an interval $[T_{m_1}, T_{n_1}]$ the interval valued function can be created as

$k_1(\eta) = (T_{m_1})^{1-\eta}(T_{n_1})^\eta$ for $\eta \in [0,1]$, which is also called parametric form in interval figure.

Model Formulation

The population is divided into three groups: pre-adult vectors, adult female mosquitoes, and human hosts. For the *A. aegypti* pre-adult female mosquito population, two parameters—eggs and larvae—are defined within both the susceptible (S_e) and infected (I_e) populations. S_v , E_v , and I_v , which stand for the

number of susceptible, infected but not yet infectious, and infectious female mosquitoes at time t , respectively, were specified as the three parameters for the adult vector (mosquito) population. Similarly, three parameters were found for the host population (humans): S_h , I_h , and R_h . With this, integer order dynamics is now used to develop the dengue model.

$$\begin{aligned}
 \frac{dS_e}{dt} &= b_v(1 - v(\frac{I_v}{S_v + E_v + I_v})) - \omega S_e, \\
 \frac{dI_e}{dt} &= b_v v(\frac{I_v}{S_v + E_v + I_v}) - \omega I_e, \\
 \frac{dS_v}{dt} &= \omega S_e - \beta S_v \frac{I_h}{N_h} - \mu_v S_v, \\
 \frac{dE_v}{dt} &= \beta S_v \frac{I_h}{N_h} - \epsilon E_v - \mu_v E_v, \quad \dots\dots\dots(1) \\
 \frac{dI_v}{dt} &= \epsilon E_v + \omega I_e - \mu_v I_v, \\
 \frac{dS_h}{dt} &= \mu_{hb} N_h - \beta S_h \frac{I_v}{N_h} - \mu_{hd} S_h, \\
 \frac{dI_h}{dt} &= \beta S_h \frac{I_v}{N_h} - \gamma I_h - \mu_{hd} I_h, \\
 \frac{dR_h}{dt} &= \gamma I_h - \mu_{hd} R_h.
 \end{aligned}$$

Table 1: Significance of the Relevant Parameters

Parameters	Significance
b_v	Rate of oviposition of the egg
v	Vertical infection rate
ω	Pre- adult mosquito maturation rate
β	Transmission biting rate
μ_v	Death rate of adult mosquito
ϵ	Rate of incubation
γ	Human recovery rate
μ_{hb}	Human birth rate
μ_{hd}	Humandeath rate

The proposed model (1) in the imprecise environment can be changed into:

$$\frac{dS_e}{dt} = \widehat{b}_v(1 - \widehat{v}(\frac{I_v}{S_v + E_v + I_v})) - \widehat{\omega}S_e,$$

$$\begin{aligned}
\frac{dI_e}{dt} &= \widehat{b}_v \widehat{v} \left(\frac{I_v}{S_v + E_v + I_v} \right) - \widehat{\omega} I_e, \\
\frac{dS_v}{dt} &= \widehat{\omega} S_e - \widehat{\beta} S_v \frac{I_h}{N_h} - \widehat{\mu}_v S_v, \\
\frac{dE_v}{dt} &= \widehat{\beta} S_v \frac{I_h}{N_h} - \widehat{\epsilon} E_v - \widehat{\mu}_v E_v, \\
&\dots\dots\dots(2) \\
\frac{dI_v}{dt} &= \widehat{\epsilon} E_v + \widehat{\omega} I_e - \widehat{\mu}_v I_v, \\
\frac{dS_h}{dt} &= \widehat{\mu}_{hb} N_h - \widehat{\beta} S_h \frac{I_v}{N_h} - \widehat{\mu}_{hd} S_h, \\
\frac{dI_h}{dt} &= \widehat{\beta} S_h \frac{I_v}{N_h} - \widehat{\gamma} I_h - \widehat{\mu}_{hd} I_h, \\
\frac{dR_h}{dt} &= \widehat{\gamma} I_h - \widehat{\mu}_{hd} R_h.
\end{aligned}$$

Now, we take $I_l(\eta) = I_{1L}^{1-\eta} I_{1R}^\eta$ for $\eta \in [0,1]$ for an interval $[I_{1L}, I_{1R}]$. Then the above system (2) can write as follows:

$$\begin{aligned}
\frac{dS_e}{dt} &= b_{vL}^{1-\eta} b_{vR}^\eta \left(1 - v_R^{1-\eta} v_L^\eta \left(\frac{I_v}{S_v + E_v + I_v} \right) \right) - \omega_R^{1-\eta} \omega_L^\eta S_e, \\
\frac{dI_e}{dt} &= b_{vL}^{1-\eta} b_{vR}^\eta v_L^{1-\eta} v_R^\eta \left(\frac{I_v}{S_v + E_v + I_v} \right) - \omega_R^{1-\eta} \omega_L^\eta I_e, \\
\frac{dS_v}{dt} &= \omega_L^{1-\eta} \omega_R^\eta S_e - \beta_R^{1-\eta} \beta_L^\eta S_v \frac{I_h}{N_h} - \mu_{vR}^{1-\eta} \mu_{vL}^\eta S_v, \\
\frac{dE_v}{dt} &= \beta_L^{1-\eta} \beta_R^\eta S_v \frac{I_h}{N_h} - \epsilon_R^{1-\eta} \epsilon_L^\eta E_v - \mu_{vR}^{1-\eta} \mu_{vL}^\eta E_v, \\
&\dots\dots\dots(3) \\
\frac{dI_v}{dt} &= \epsilon_L^{1-\eta} \epsilon_R^\eta E_v + \omega_L^{1-\eta} \omega_R^\eta I_e - \mu_{vR}^{1-\eta} \mu_{vL}^\eta I_v, \\
\frac{dS_h}{dt} &= \mu_{hbL}^{1-\eta} \mu_{hbR}^\eta N_h - \beta_R^{1-\eta} \beta_L^\eta S_h \frac{I_v}{N_h} - \mu_{hdR}^{1-\eta} \mu_{hdL}^\eta S_h, \\
\frac{dI_h}{dt} &= \beta_L^{1-\eta} \beta_R^\eta S_h \frac{I_v}{N_h} - \gamma_R^{1-\eta} \gamma_L^\eta I_h - \mu_{hdR}^{1-\eta} \mu_{hdL}^\eta I_h, \\
\frac{dR_h}{dt} &= \gamma_L^{1-\eta} \gamma_R^\eta I_h - \mu_{hdR}^{1-\eta} \mu_{hdL}^\eta R_h.
\end{aligned}$$

Analysis of the System

We have two equilibrium point say trivial disease-free equilibrium $E_0 = (0, 0, 0, 0, 0, S_h^0, 0, 0)$ and biologically realistic equilibrium

$$E_1 = (S_e^*, 0, S_v^*, 0, 0, S_h^*, 0, 0) \text{ where } S_h^0 = \frac{\mu_{hbL}^{1-\eta} \mu_{hbR}^{\eta} N_h}{\mu_{hdR}^{1-\eta} \mu_{hdL}^{\eta}}, S_e^* = \frac{b_{vL}^{1-\eta} b_{vR}^{\eta}}{\omega_R^{1-\eta} \omega_L^{\eta}}, S_v^* = \frac{b_{vL}^{1-\eta} b_{vR}^{\eta}}{\mu_{vR}^{1-\eta} \mu_{vL}^{\eta}}, S_h^* = \frac{\mu_{hbL}^{1-\eta} \mu_{hbR}^{\eta} N_h}{\mu_{hdR}^{1-\eta} \mu_{hdL}^{\eta}}.$$

Using the next-generation matrix approach [52, 53] we have,

$$\mathcal{FV}^{-1} = \begin{bmatrix} 0 & \frac{\beta_L^{1-\eta} \beta_R^{\eta}}{\mu_{vR}^{1-\eta} \mu_{vL}^{\eta}} & \frac{\beta_L^{1-\eta} \beta_R^{\eta} \omega_L^{1-\eta} \omega_R^{\eta}}{\mu_{vR}^{1-\eta} \mu_{vL}^{\eta} (\omega_L^{1-\eta} \omega_R^{\eta} + \mu_{vR}^{1-\eta} \mu_{vL}^{\eta})} & \frac{\beta_L^{1-\eta} \beta_R^{\eta}}{\mu_{vR}^{1-\eta} \mu_{vL}^{\eta}} \\ 0 & v_L^{1-\eta} v_R^{\eta} & \frac{v_L^{1-\eta} v_R^{\eta} \epsilon_L^{1-\eta} \epsilon_R^{\eta}}{(v_L^{1-\eta} v_R^{\eta} + \mu_{vR}^{1-\eta} \mu_{vL}^{\eta})} & v_L^{1-\eta} v_R^{\eta} \\ \frac{\beta_L^{1-\eta} \beta_R^{\eta} N_v}{N_h (\gamma + \mu_{hd})} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}.$$

Therefore,

$$R_0 = \frac{v_L^{1-\eta} v_R^{\eta}}{2} + \frac{1}{2} \sqrt{(v_L^{1-\eta} v_R^{\eta})^2 + \frac{4(\beta_L^{1-\eta} \beta_R^{\eta})^2 \omega_L^{1-\eta} \omega_R^{\eta} N_m}{N_h (\gamma_L^{1-\eta} \gamma_R^{\eta} + \mu_{hdR}^{1-\eta} \mu_{hdL}^{\eta}) \mu_{vR}^{1-\eta} \mu_{vL}^{\eta} (\epsilon_L^{1-\eta} \epsilon_R^{\eta} + \mu_{vR}^{1-\eta} \mu_{vL}^{\eta})}}.$$

Numerical Study

In this section, we verify and validate the analytical results of our model system using meticulous numerical simulations. We used the math programs Matlab (2018) and Matcont to discuss the solution of the proposed system.

Table 2: Displays several variables that were utilized to simulate the system (3).

Parameters	Values (For Planer)
$\widehat{b_v}$	[0.51, 0.61]
\widehat{v}	[0.37, 0.47]
\widehat{w}	[0.33, 0.44]
$\widehat{\beta}$	[0.066, 0.076]
N_h	0.051
$\widehat{\gamma}$	[1.23, 1.33]
$\widehat{\epsilon}$	[0.45, 0.55]
$\widehat{\mu_v}$	[0.57, 0.67]
$\widehat{\mu_{hb}}$	[8.81, 8.91]
$\widehat{\mu_{hd}}$	[0.87, 0.97]

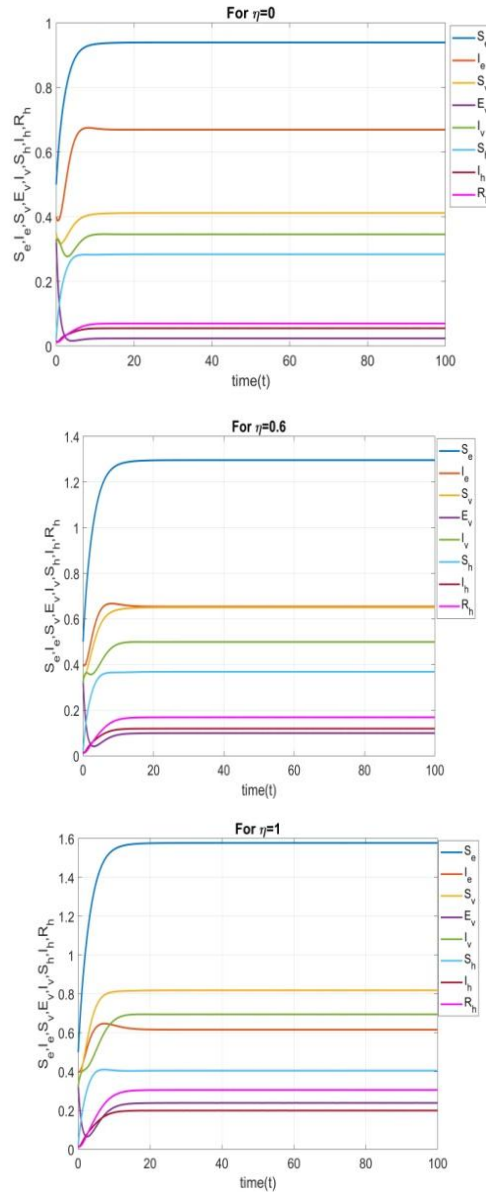


Fig. 1: Depicts the stable nature at E_1 for several values of ρ .

Conclusion

A dengue model with temperature effects under uncertainty about intervals has been studied. It talks about the model's dynamic properties in the context of an unpredictable setting. Temperature affects dengue and other infections spread by mosquitoes. Our examination of the known relationships between temperature and dengue fever lends credence to the hypothesis that temperature has a nonlinear effect on a range of ecological processes. This encompasses little or adverse impacts at both low and high temperatures, as well as noteworthy favourable impacts within a

certain intermediate temperature range. *Aedes albopictus*, which lives at a lower optimal transmission temperature than *Aedes aegypti*, may be a factor in the spread of dengue fever in people, which might account for the colder anticipated optimum temperature. A few human instances from the evaluated study provide more evidence in favour of this theory. We were not able to verify this idea, nonetheless, due to contradictory data between research about the species in charge of transmission. In further studies, the authors want to further examine ecological models utilizing neotropical habitats and suggest medical research frameworks employing mathematical modelling methodologies.

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The Role of Eigenvalues and Eigenvectors in Real-World Problems

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Abstract

Eigenvalues and eigenvectors are fundamental concepts in linear algebra with profound applications in diverse real-world fields, from physics and engineering to economics and data science. This paper explores the importance of eigenvalues and eigenvectors in solving various practical problems. Their application spans structural engineering, quantum mechanics, machine learning, and image processing, among others. We examine how eigenvectors, representing directions of transformation, and eigenvalues, representing the magnitude of those transformations, help in simplifying complex problems, predicting system behavior, and extracting meaningful patterns from large data sets. By understanding these concepts, we can appreciate their transformative role in the applied sciences and engineering.

Introduction

Eigenvalues and eigenvectors are concepts that arise from the study of linear transformations. In simpler terms, when a matrix represents a transformation in space, eigenvectors are those vectors that, when transformed by the matrix, do not change direction; they are merely scaled by a factor, which is the eigenvalue. These concepts, though initially abstract, have vast applications in solving real-world problems across various domains.

This paper explores the significant role of eigenvalues and eigenvectors in several fields, offering insights into their practical applications. We will look at how

they are used to solve systems of differential equations, perform data analysis, optimize engineering designs, and even make predictions in machine learning.

Eigenvalues and Eigenvectors in Physics and Engineering

- **Vibrations and Structural Analysis**

In engineering, particularly in the analysis of mechanical structures, eigenvalues and eigenvectors are essential in determining natural frequencies and mode shapes of structures. For instance, in the analysis of vibrations of bridges, buildings, and other mechanical systems, the equation governing these vibrations can be expressed in the form of a matrix. The eigenvalues in this context represent the natural frequencies of the system, while the eigenvectors represent the mode shapes.

The solution to this eigenvalue problem is fundamental in designing structures that can withstand dynamic forces such as earthquakes or high winds. If the frequency of external forces matches the natural frequency of a structure, resonance can occur, potentially leading to catastrophic failure. Engineers use eigenvalue analysis to avoid such resonance and design safe structures.

- **Quantum Mechanics**

In quantum mechanics, eigenvalues and eigenvectors are deeply embedded in the foundational theory. The Schrödinger equation, which governs the behavior of quantum systems, is typically solved using the concept of eigenvalue problems. The solutions to this equation give the allowed energy levels of a quantum system, with the eigenvalues representing the possible energy levels and the eigenvectors corresponding to the quantum states associated with these energies.

The importance of eigenvalues in quantum mechanics is critical in understanding atomic, molecular, and subatomic behavior, directly influencing fields such as material science, chemistry, and nuclear physics.

Data Science and Machine Learning

- **Principal Component Analysis (PCA)**

One of the most well-known applications of eigenvalues and eigenvectors in data science is Principal Component Analysis (PCA). PCA is a dimensionality reduction technique used to simplify large data sets by transforming them into a set of orthogonal components that capture the most significant variance in the data. These components are derived from the eigenvectors of the covariance matrix of the data, while the eigenvalues represent the amount of variance explained by each component.

PCA is widely used in fields like image compression, anomaly detection, and exploratory data analysis, helping to make sense of complex data by reducing its dimensionality without losing critical information.

- **Spectral Clustering**

Eigenvalues and eigenvectors also play a crucial role in spectral clustering, a method used in graph theory and machine learning to group data points into clusters. By using the eigenvectors of the graph Laplacian matrix, spectral clustering identifies clusters that minimize the within-cluster distances. This method is particularly effective for data that is non-linearly separable and has complex relationships between data points.

Image Processing and Computer Vision

- **Eigenfaces in Facial Recognition**

Eigenvalues and eigenvectors are used in facial recognition systems, specifically in the method known as Eigenfaces. By representing the facial features of individuals as vectors in a high-dimensional space, the algorithm computes the eigenvectors of the covariance matrix of these vectors. The eigenfaces correspond to the primary features of a face, and they are used to reduce the dimensionality of the problem, making recognition more efficient and accurate.

This method is extensively used in security systems, social media platforms, and personal identification technologies.

- **Image Compression**

In image processing, eigenvalues and eigenvectors are used in techniques like Singular Value Decomposition (SVD) for image compression. SVD decomposes a matrix representing an image into three matrices, with the eigenvalues reflecting the importance of the singular values in representing the image. By retaining only the most significant singular values, the image can be compressed with minimal loss of quality.

Optimization and Economics

- **Portfolio Optimization**

In finance and economics, eigenvalues and eigenvectors are instrumental in portfolio optimization problems. The covariance matrix of asset returns is used to calculate the eigenvectors and eigenvalues, which in turn help in determining the optimal allocation of assets to minimize risk and maximize return.

By analyzing the eigenvalues of the covariance matrix, investors can understand the risk and return characteristics of different assets and make informed investment decisions.

- **Markov Chains and Population Modeling**

In population dynamics and economic modeling, eigenvalues and eigenvectors are used in analyzing Markov chains and predicting the long-term behavior of a system. The eigenvectors of the transition matrix represent the steady-state

distribution of the system, and the eigenvalues help determine the speed at which the system converges to equilibrium.

Conclusion

Eigenvalues and eigenvectors are not just abstract concepts but are foundational tools for solving a wide array of real-world problems. Their applications in engineering, physics, data science, economics, and many other fields showcase their versatility and importance. By understanding the principles behind eigenvalues and eigenvectors, professionals and researchers can model complex systems, analyze large datasets, and optimize processes, leading to more efficient solutions and innovative technologies.

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Current Modified Higher-Order Evolution Equation for Broader Bandwidth Gravity-Capillary Waves

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Abstract

This work presents a detailed study of a higher-order evolution equation governing capillary-gravity waves propagating on a finite-depth layer of water with a depth-uniform current. The combined influence of surface tension, gravity, and underlying uniform flow introduces complexities to wave dynamics that necessitate an advanced mathematical framework. Starting from the fundamental governing equations of fluid motion, a systematic derivation of the higher-order nonlinear evolution equation is achieved through a perturbation expansion method, accommodating broader bandwidth wave packets. The equation captures the intricate interplay between nonlinearity, dispersion, and the influence of the uniform current. Analysis of the equation demonstrates its capacity to describe phenomena such as wave modulation, energy transfer, and stability under varying physical conditions. Special attention is given to how the uniform current modifies the dispersion characteristics, leading to significant alterations in wave behavior and interaction. This study offers insights into practical applications like coastal engineering, wave energy harnessing, and understanding natural water wave dynamics under the influence of surface currents. The higher-order model provides a robust tool for examining realistic capillary-gravity wave scenarios and their interactions in both theoretical and applied contexts.

Keywords: Nonlinear Evolution Equation, Capillary-Gravity Waves, Broader Bandwidth, Modulational Instability.

Introduction

In the studies of the nonlinear evolution of deep-water waves, nonlinear Schrödinger equation (NLSE) is generally used as it can properly reflect the sideband instability, that is, the Benjamin-Feir instability. In general, capillary-gravity waves are generated by wind which produces a shear flow in the topmost layer of the water and as a result these waves move in the presence of vorticity. These waves play a momentous role in the development of wind waves, contribute partially to the ocean surface stress and therefore take part in ocean-sea momentum transfer. Proper representation of the surface stress is useful in modelling and predicting sea wave dynamics. The instability of finite amplitude capillary-gravity waves has been studied by many authors. Djordjevic and Redekopp [1] and Hogan [2] have investigated cubic nonlinear envelope equations for finite and infinite depths of water respectively and studied the sideband instability (Benjamin-Feir instability) of progressive capillary-gravity waves. Dhar and Das [3] have investigated the fourth-order nonlinear evolution equation (NLEE) for two surface capillary-gravity waves on deep water and stability analysis is then presented for two Stokes waves. Debsarma and Das [4] have also derived two coupled fourth-order NLEEs in deep water including the effect of thin thermocline for capillary-gravity waves. After reducing these two equations to a single equation in the case of oblique plane wave perturbation, they have studied the stability analysis for a uniform wave train. Although the stability analysis made from fourth-order NLSE gives excellent results compared to the third-order equation, the limitation in wave bandwidth severely restricts the applicability of third- and fourth-order Schrödinger equations for three-dimensional sea waves in two ways. First, the ocean wave spectra from the continental shelf are often bandwidth restricted but have bandwidths exceeding the above restriction. Second, these evolution equations have instability regions for a finite amplitude wave extending outside the narrow bandwidth constraint. Keeping this view, Trulsen and Dysthe [5] have derived a higher-order NLEE for the broader bandwidth surface gravity waves on deep water in which the wave bandwidth and nonlinearity have been considered as $O(\epsilon^{1/2})$ and $O(\epsilon)$ respectively. Following Trulsen and Dysthe [5], we take finite depth, deep water, and infinite depth as $(kh)^{-1}$ being $O(1)$, $O(\epsilon)$ and 0 respectively.

According to Trulsen and Dysthe [5], one avenue of interest is to include some new linear terms to the fourth-order NLEE derived by Dysthe [6], which have increased considerably the resolution in spectral bandwidth. In this paper, we extend the analysis of Trulsen and Dysthe [5] to include the effect of capillarity. The objective and the novelty of this paper is to derive a new higher-order NLEE for a broader bandwidth and to develop a weakly nonlinear theory of the periodic capillary-gravity waves on finite depth of water under the action of depth uniform current (DUC).

The Governing Equations and The Fourth-order Evolution Equation

We adopt the geometric setup of a Cartesian coordinate frame (Oxyz), where z axis is directed upward in the opposing direction of gravity g. In this framework, the undisturbed free surface is represented by $z=0$, while the disturbed free surface is represented by $z=\zeta(x,y,t)$. We suppose that the waves flow steadily on a DUC v, where v denotes the speed of the current at the free surface and moves in the positive direction of the x axis. For describing the irrotational motion of gravity waves on the surface of deep water, we take the following governing equations into consideration:

$$\nabla^2 \phi = 0 \text{ in } -h < z < \zeta(x, y, t) \quad (1)$$

$$\phi_z - \zeta_t - v\zeta_x = \phi_x \zeta_x + \phi_y \zeta_y \text{ at } z = \zeta \quad (2)$$

$$\phi_t + v\zeta_x + \zeta = -\frac{1}{2}(\nabla\phi)^2 + \kappa \frac{(\zeta_x^2 \zeta_{yy} + \zeta_y^2 \zeta_{xx} - 2\zeta_x \zeta_y \zeta_{xy} + \zeta_{xx} + \zeta_{yy})}{(1 + \zeta_x^2 + \zeta_y^2)^{\frac{3}{2}}} \text{ at } z = \zeta \quad (3)$$

$$\text{Also } \phi_z = 0, \text{ at } z = -h, \quad (4)$$

where $\phi(x, y, z, t)$ is the velocity potential of waves, $\zeta(x, y, t)$ is the undulating free surface, ρ is the density of fluid and $\nabla \equiv \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right)$. The above equations have been made dimensionless by the following transformations

$$\tilde{\phi} = \sqrt{\frac{k_0^3}{g}} \phi, \tilde{\zeta} = k_0 \zeta, (\tilde{x}, \tilde{y}, \tilde{z}) = (k_0 x, k_0 y, k_0 z), \tilde{t} = \omega t, \kappa = \frac{T k_0^2}{\rho g},$$

where k_0 is some characteristic wavenumber, g is the gravitational acceleration and T is the surface tension coefficient of the bulk fluid. In subsequent analysis, all these dimensionless quantities will be written with their tilde deleted.

The solutions of the above-mentioned equations can be expressed as

$$B = \bar{B} + \sum_{p=1}^{\infty} [B_p \exp\{i p(kx - \omega t)\}] + \text{c.c.} \quad (5)$$

where B indicates ϕ , ζ ; c.c. means complex conjugate and k, ω are the wavenumber and frequency of the primary wave respectively. Here, the slow drift $\bar{\phi}$ and set down $\bar{\zeta}$ as well as the harmonic amplitudes ϕ_p, ζ_p ($p = 1, 2, \dots$) and their complex conjugates are functions of the slow modulation variables $\epsilon x, \epsilon y$ and ϵt , where ϵ is a slow ordering parameter. Again, $\bar{\phi}$ depends on the slow variable ϵz , while ϕ_p ($p = 1, 2, \dots$) and their complex conjugates are the function of z . We consider the fourth-order NLEE for narrow bandwidth when the motion is weakly nonlinear, so that $0 < \epsilon \ll 1$ subject to the assumption as follows

$$k_0 a = O(\epsilon), \frac{|\nabla k|}{k_0} = O(\epsilon), (k_0 h)^{-1} = O(\epsilon)$$

The linear dispersion relation with $l = 0$ is given by

$$f(\omega, k, l) = \omega^2 - \sqrt{k^2 + l^2} \{1 + \kappa(k^2 + l^2)\} = 0,$$

where ω, k represent the carrier frequency and wave number respectively.

By a standard procedure (Dhar and Das [7]) we obtain the fourth-order coupled NLEEs for the free surface elevation ζ , where $\zeta = \zeta_{11} + \epsilon \zeta_{12}$, and $\bar{\Phi}$ as follows

$$i \left(\frac{\partial \zeta}{\partial \tau} + c_g \frac{\partial \zeta}{\partial x} \right) - \gamma_1 \frac{\partial^2 \zeta}{\partial x^2} + \gamma_2 \frac{\partial^2 \zeta}{\partial y^2} + i \left(\gamma_3 \frac{\partial^3 \zeta}{\partial x^3} + \gamma_4 \frac{\partial^3 \zeta}{\partial x \partial y^2} \right) = \mu_1 |\zeta|^2 \zeta^* + i \left(\mu_2 |\zeta|^2 \frac{\partial \zeta}{\partial x} + \mu_3 \zeta^2 \frac{\partial \zeta^*}{\partial x} \right) + \zeta \frac{\partial \bar{\Phi}}{\partial x} \quad (6)$$

$$\nabla^2 \bar{\Phi} = 0 \text{ for } -h < z < 0 \quad (7)$$

$$\frac{\partial \bar{\Phi}}{\partial z} = 2 \frac{\partial}{\partial x} (|\zeta|^2) \text{ for } z = 0 \quad (8)$$

$$\frac{\partial \bar{\Phi}}{\partial z} = 0 \text{ for } z = -h \quad (9)$$

For $\kappa = 0$ and $v = 0$ the equation (6) is identical to an equation (10) of Trulsen and Dysthe [5].

Typically, one assumes that the wave steepness and the bandwidth are of the identical order of magnitude $O(\epsilon)$, for which both the nonlinear and dispersive effects balance at the fourth order $O(\epsilon^4)$.

Stability Analysis

A solution for the uniform wave train of the NLEE is given by

$$\zeta = \frac{\zeta_0}{2} e^{-i\mu_1 \zeta_0^2 t/4}, \bar{\Phi} = \Phi_0,$$

where ζ_0, Φ_0 are real constants.

We assume the perturbations on this solution as follows

$$\zeta = \frac{\zeta_0}{2} (1 + \zeta') e^{i(\theta' - \mu_1 \zeta_0^2 t/4)}, \bar{\Phi} = \Phi_0 (1 + \phi'), \quad (10)$$

where ζ', θ' are infinitesimal perturbations of the amplitude and phase respectively and ϕ' is a real small perturbation of $\bar{\Phi}$. Inserting (10) in equation (6) we get the two linear equations in ζ' and θ' . Now we take the plane wave solution of the above two equations given by

$$\begin{pmatrix} \zeta' \\ \theta' \end{pmatrix} = \begin{pmatrix} \zeta \\ \theta \end{pmatrix} e^{i(\lambda x + \mu y - \Omega t)} + \text{c. c.}$$

$$\phi' = \hat{\Phi} \left\{ e^{i(\lambda x + \mu y - \Omega t)} + \text{c. c.} \right\} \frac{\cos \bar{k}(z+h)}{\cosh(\bar{k}h)}, \quad \bar{k}^2 = \lambda^2 + \mu^2$$

The perturbed wave numbers λ, μ and the perturbed frequency Ω satisfy the following nonlinear dispersion relation

$$\left\{\bar{S}_1 + \frac{(\mu_2 + \mu_3)}{4} \zeta_0^2 \lambda\right\} \left\{\bar{S}_1 + \frac{(\mu_2 - \mu_3)}{4} \zeta_0^2 \lambda\right\} = \bar{S}_2 \left\{\bar{S}_2 - \frac{\mu_1}{2} \zeta_0^2 + \frac{\lambda^2 \zeta_0^2}{k \tanh(kh)}\right\}, \quad (11)$$

where $\bar{S}_1 = \Omega - c_g \lambda + \gamma_3 \lambda^3 + \gamma_4 \lambda \mu^2$ and $\bar{S}_2 = \gamma_1 \lambda^2 - \gamma_2 \mu^2$ and c_g is the group velocity of the carrier wave.

The solution of (11) is given by

$$\bar{S}_1 = -\frac{\mu_2}{4} \zeta_0^2 \lambda \pm \sqrt{\bar{S}_2 \left\{\bar{S}_2 - \frac{\mu_1}{2} \zeta_0^2 + \frac{\lambda^2 \zeta_0^2}{k \tanh(kh)}\right\}} \quad (12)$$

From (12) the instability occurs if

$$\bar{S}_2 \left\{\bar{S}_2 - \frac{\mu_1}{2} \zeta_0^2 + \frac{\lambda^2 \zeta_0^2}{k \tanh(kh)}\right\} < 0 \quad (13)$$

If the condition (13) is satisfied, the perturbed frequency Ω will be a complex valued and the growth rate of instability represented by the imaginary part Ω_i of Ω becomes

$$\Omega_i = \sqrt{(\gamma_1 \lambda^2 - \gamma_2 \mu^2) \left(\frac{\mu_1}{2} \zeta_0^2 - \gamma_1 \lambda^2 + \gamma_2 \mu^2 - \frac{\lambda^2 \zeta_0^2}{k \tanh(kh)} \right)}. \quad (14)$$

Higher-order Evolution Equation for Broader Bandwidth

To obtain a better resolution in bandwidth, following Trulsen and Dysthe [5], we take the following assumptions

$$k_0 a = O(\epsilon), \frac{|\nabla \mathbf{k}|}{k_0} = O(\epsilon^{1/2}), (k_0 h)^{-1} = O(\epsilon^{1/2})$$

We use here the same harmonic expansions (5) for the velocity potential ϕ and the surface elevation ζ . In this case $\bar{\phi}, \bar{\zeta}, \phi_p, \zeta_p$ ($p = 1, 2, \dots$) are functions of the new slightly faster modulation variables $\epsilon^{1/2}t$ and $\epsilon^{1/2}x$, $\epsilon^{1/2}y$ and also $\bar{\phi}$ depends on the new slightly faster variable $\epsilon^{1/2}z$.

Now we take the following perturbation expansions

$$E_1 = \sum_{p=1}^{\infty} \epsilon^{p/2} E_{1p}, \quad E_2 = \sum_{p=2}^{\infty} \epsilon^{p/2} E_{2p},$$

where E_j stands for B_j and ζ_j , $B_j = (\phi_j)_{z=0}$, $j = 1, 2$.

Herein, we keep the same accuracy in nonlinearity as in equation (6) and it is to be noted that as all the fourth-order contributions to this equation are not quartically nonlinear, it is sufficient to consider the new evolution equation for broader bandwidth only up to $O(\epsilon^{7/2})$.

Computing the perturbation analysis as in Dhar and Das [7], we obtain eventually the coupled NLEEs in terms of ζ and $\bar{\phi}$ for broader bandwidth as follows

$$i \left(\frac{\partial \zeta}{\partial \tau} + c_g \frac{\partial \zeta}{\partial x} \right) - \gamma_1 \frac{\partial^2 \zeta}{\partial x^2} + \gamma_2 \frac{\partial^2 \zeta}{\partial y^2} + i \left(\gamma_3 \frac{\partial^3 \zeta}{\partial x^3} + \gamma_4 \frac{\partial^3 \zeta}{\partial x \partial y^2} \right) + \gamma_5 \frac{\partial^4 \zeta}{\partial x^4} + \gamma_6 \frac{\partial^4 \zeta}{\partial x^2 \partial y^2} + \gamma_7 \frac{\partial^4 \zeta}{\partial y^4} + i \left(\gamma_8 \frac{\partial^5 \zeta}{\partial x^5} + \gamma_9 \frac{\partial^5 \zeta}{\partial x^3 \partial y^2} + \gamma_{10} \frac{\partial^5 \zeta}{\partial x \partial y^4} \right) = \mu_1 |\zeta|^2 \zeta^* + i \left(\mu_2 |\zeta|^2 \frac{\partial \zeta}{\partial x} + \mu_3 \zeta^2 \frac{\partial \zeta^*}{\partial x} \right) + \zeta \frac{\partial \bar{\Phi}}{\partial x} \quad (15)$$

$$\nabla^2 \bar{\Phi} = 0 \text{ for } -h < z < 0 \quad (16)$$

$$\frac{\partial \bar{\Phi}}{\partial z} = 2 \frac{\partial}{\partial x} (|\zeta|^2) \text{ for } z = 0 \quad (17)$$

$$\frac{\partial \bar{\Phi}}{\partial z} = 0 \text{ for } z = -h, \quad (18)$$

where the coefficients are given in Appendix.

In the new NLSE for broader bandwidth, we have assumed that the wave steepness is of order $O(\epsilon)$, while the wave bandwidth is of order $O(\epsilon^{1/2})$ for which the nonlinear and the dispersive effects balance at the order $O(\epsilon^{7/2})$.

In the absence of capillarity, the equation (15) reduces to an equation (21) of Trulsen and Dysthe [5].

Proceeding as in section 3, we obtain the nonlinear dispersion relation as follows

$$\left\{ R_1 + \frac{(\mu_2 + \mu_3)}{4} \zeta_0^2 \lambda \right\} \left\{ R_1 + \frac{(\mu_2 - \mu_3)}{4} \zeta_0^2 \lambda \right\} = R_2 \left\{ R_2 - \frac{\mu_1}{2} \zeta_0^2 + \frac{\lambda^2 \zeta_0^2}{\bar{k} \tanh(\bar{k}h)} \right\}, \quad (19)$$

Where,

$$R_1 = \Omega - c_g \lambda + \gamma_3 \lambda^3 + \gamma_4 \lambda \mu^2 - \gamma_8 \lambda^5 - \gamma_9 \lambda^3 \mu^2 - \gamma_{10} \lambda \mu^4, \quad (20)$$

$$R_2 = \gamma_1 \lambda^2 - \gamma_2 \mu^2 + \gamma_5 \lambda^4 + \gamma_6 \lambda^2 \mu^2 + \gamma_7 \mu^4.$$

The solution of (19) is given by

$$R_1 = -\frac{\mu_2}{4} \zeta_0^2 \lambda \pm \sqrt{R_2 \left\{ R_2 - \frac{\mu_1}{2} \zeta_0^2 + \frac{\lambda^2 \zeta_0^2}{\bar{k} \tanh(\bar{k}h)} \right\}} \quad (21)$$

Using (20) the equation (19) can be expressed as

$$\Omega =$$

$$c_g \lambda - \gamma_3 \lambda^3 - \gamma_4 \lambda \mu^2 + \gamma_8 \lambda^5 + \gamma_9 \lambda^3 \mu^2 + \gamma_{10} \lambda \mu^4 - \frac{\mu_2}{4} \zeta_0^2 \lambda \pm$$

$$\sqrt{R_2 \left\{ R_2 - \frac{\mu_1}{2} \zeta_0^2 + \frac{\lambda^2 \zeta_0^2}{\bar{k} \tanh(\bar{k}h)} \right\}} \quad (22)$$

If we set $\kappa = 0$, then the equation (22) reduces to an equation equivalent to equation (25) of Trulsen and Dysthe [5].

It follows from (22) that for instability we have

$$R_2 \left\{ R_2 - \frac{\mu_1}{2} \zeta_0^2 + \frac{\lambda^2 \zeta_0^2}{\bar{k} \tanh(\bar{k}h)} \right\} < 0 \quad (23)$$

The instability growth rate Ω_i , which is the imaginary part of the perturbed frequency Ω , is given by

$$\Omega_i = \sqrt{R_2 \left(\frac{\mu_1}{2} \zeta_0^2 - R_2 - \frac{\lambda^2 \zeta_0^2}{k \tan h(\bar{k}h)} \right)} \quad (24)$$

Conclusion

The development of a higher-order evolution equation for capillary-gravity waves, incorporating a broader bandwidth and the effects of a depth-uniform current, represents a significant advancement in understanding wave dynamics in complex fluid environments. This enhanced model addresses the limitations of traditional approaches, which often focus on narrow bandwidths and simplified current effects, providing a more comprehensive description of wave behavior. By extending the evolution equation to account for a wider range of wave frequencies and incorporating the influence of a uniform current, the model offers improved accuracy in predicting wave properties such as amplitude, phase speed, and frequency spectrum. The results indicate that the uniform current has a notable impact on these properties, altering wave characteristics in ways that previous models might not fully capture. This advancement has practical implications for fields such as coastal engineering, marine navigation, and offshore operations, where precise wave predictions are crucial for designing structures, managing navigation routes, and ensuring safety. The higher-order model's ability to account for complex interactions between capillary forces, gravity, and currents enhances its utility for real-world applications. Future research should focus on validating this model with empirical data and exploring its applicability to various environmental conditions and wave scenarios. Continued development in this area will contribute to more accurate and reliable wave forecasting, ultimately supporting better decision-making in maritime and coastal management.

Appendix

$$\begin{aligned} \gamma_1 &= \frac{B}{2\sigma f_\sigma^2(1+\kappa)}, \gamma_2 = \frac{1+3\kappa}{\sigma f_\sigma^2}, \gamma_3 = \frac{2AB-\kappa f_\sigma^4}{2\sigma f_\sigma^4(1+\kappa)}, \gamma_4 = \frac{(1-3\kappa)f_\sigma^2-2(1+3\kappa)A}{4\sigma f_\sigma^2(1+\kappa)}, \\ \gamma_5 &= \frac{A^4+4A^2B-6A^2\kappa f_\sigma^2-2A\kappa f_\sigma^4+9\kappa^2 f_\sigma^2}{2\sigma f_\sigma^6(1+\kappa)}, \gamma_6 = \frac{(1-3\kappa)A f_\sigma^2-(1+3\kappa)(2A^2+B)-\{(f_\sigma)^4/2\}}{2\sigma f_\sigma^4(1+\kappa)}, \\ \gamma_7 &= \frac{2(1+3\kappa)^2+(1-3\kappa)f_\sigma^2}{16\sigma f_\sigma^2(1+\kappa)}, \gamma_8 = \frac{-2AB(4A^2+3B)+4B\kappa f_\sigma^4+4uA\kappa f_\sigma^5+2\{f_k^2-(u^2-3\kappa)f_\sigma^2\}\kappa f_\sigma^4}{2\sigma h_\sigma^8(1+\kappa)}, \\ \gamma_9 &= \frac{(1+3\kappa)(4A^3+6AB-\kappa f_\sigma^4)-(1-3\kappa)(2A^2 f_\sigma^2+B h_\sigma^2)+A f_\sigma^4-\{(f_\sigma)^6/2\}}{2\sigma f_\sigma^6(1+\kappa)}, \\ \gamma_{10} &= \frac{-2(1-3\kappa)A f_\sigma^2-12(1+3\kappa)^2 A+4(1+3\kappa)(1-3\kappa)f_\sigma^2+3(1-\kappa)f_\sigma^4}{16\sigma f_\sigma^4(1+\kappa)}, \mu_1 = \frac{1}{\sigma f_\sigma^2} \left\{ \frac{4(1+\kappa)(2-\kappa)}{1-2\kappa} - 3\kappa \right\} \\ \mu_2 &= \frac{3(4\kappa^4+4\kappa^3-9\kappa^2+\kappa-8)}{\sigma f_\sigma^2(1+\kappa)(1-2\kappa)^2}, \mu_3 = \frac{(2\kappa^2+\kappa+8)(1-\kappa)}{2\sigma f_\sigma^2(1+\kappa)(1-2\kappa)}, A = f_k, B = f_k^2 - 3\kappa f_\sigma^2, f_k = \frac{\partial f}{\partial k}, f_\sigma = \frac{\partial f}{\partial \sigma}. \end{aligned}$$

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Nomenclature

h	Uniform depth of the fluid
ϕ	Velocity potential of capillary-gravity waves
ζ	Undulating free surface
ρ	Density of fluid
k_0	Characteristic wave number
g	Gravitational acceleration
T	Surface tension coefficient of the bulk fluid
ϵ	Slow ordering parameter
ω	Carrier frequency
k	Carrier wave number
c_g	Group velocity
ζ_0	Wave steepness
(λ, μ)	Perturbed wave numbers
Ω	Perturbed frequency
Ω_i	Growth rate of instability



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Nanotechnology in Shrimp Farming: A Tool for Disease Prevention and Sustainable Management

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Abstract

Shrimp farming is a crucial sector in aquaculture worldwide; nonetheless, it encounters ongoing challenges associated with disease outbreaks that jeopardize shrimp health and farm output. The application of antibiotics and chemicals to manage these infections, although beneficial, has generated much apprehension regarding antibiotic resistance, environmental contamination, and food safety. Consequently, there is an immediate necessity for new, sustainable disease management systems. Nanotechnology, characterized by its distinctive features at the molecular and nanoscale, presents a viable resolution to these difficulties. Nanomaterials, including nanoparticles, nanocomposites and nanosensors, demonstrate significant potential in advancing shrimp health management by enhancing disease prevention, pathogen detection, and water quality regulation. Moreover, nanotechnology offers more precise, efficient, and eco-friendly alternatives to traditional therapies, diminishing dependence on hazardous chemicals. This paper emphasizes the necessity of nanotechnology as an alternative therapeutic approach in shrimp aquaculture, concentrating on its prospective uses, advantages, and obstacles. It delves into the potential of nanotechnology to transform shrimp disease control, providing more sustainable, effective, and economical solutions for the aquaculture sector.

Keywords: Nanotechnology, Shrimp farming, Disease management, Aquaculture health, Antibiotic resistance.

Introduction

Shrimp farming is an essential component of aquaculture globally, considerably contributing to the world's seafood supply and sustaining the livelihoods of millions. Nonetheless, the shrimp farming sector encounters ongoing difficulties in disease management, resulting in significant economic losses, environmental deterioration, and risk to food security [1]. Shrimps are very susceptible to numerous infectious diseases, encompassing bacterial, viral, and fungal infections, which frequently end up in elevated mortality rates, diminished production efficiency, and the necessity for extensive application of antibiotics and chemicals. Conventional disease management approaches in shrimp aquaculture, including the application of antibiotics, vaccines, and chemical interventions, have demonstrated efficacy in mitigating certain outbreaks. Nonetheless, these methods frequently entail considerable disadvantages, such as the development of antibiotic resistance, ecological pollution, and adverse effects on the adjacent ecology. Furthermore, the identification and control of diseases in shrimp farms are hindered by a rapid spread of infections, inadequate diagnostic techniques, and difficulties in reducing disease transmission within congested farming settings [2]. Nanotechnology, the discipline of manipulating matter at the molecular and atomic levels, has surfaced as an effective approach toward addressing these difficulties. Nanotechnology, by its capacity to improve material properties at the nanoscale, provides novel methods for disease detection, prevention, and treatment in shrimp aquaculture [3]. Nanomaterials, including nanoparticles, nanocomposites, and nanobiosensors, are essential instruments for enhancing the precision and efficacy of disease management, diminishing dependence on hazardous chemicals, and fostering sustainable aquaculture practices. This review intends to explore the significance of nanotechnology in disease management within shrimp farming, emphasizing its applications in diagnostics, antimicrobial therapies, and disease prevention methods. This analysis of contemporary research and advancements will underscore nanotechnology's potential to transform shrimp farming into a more sustainable, efficient, and resilient industry in the face of increasing challenges from infectious illnesses. Additionally, we will examine the environmental, economic, and regulatory ramifications of incorporating nanotechnology into shrimp farming operations and highlight critical areas requiring further research to ensure its safe and beneficial application.

Challenges

Disease management in shrimp farming is a crucial concern that directly impacts shrimp health, farm output, and the industry's overall sustainability. Shrimp aquaculture is especially susceptible to various infectious diseases, and the complexities associated with effective disease management are intricate and multifaceted. Notable diseases impacting shrimp include White Spot Syndrome Virus

(WSSV), Early Mortality Syndrome (EMS), Vibriosis, Yellow Head Disease, and Infectious Myonecrosis [4]. These illnesses can result in elevated death rates, occasionally decimating whole herds within days, hence causing substantial economic losses for producers. Shrimp farmers frequently utilize antibiotics and various chemical treatments to manage disease outbreaks. The frequent and excessive application of antibiotics in shrimp farming has resulted in the development of antimicrobial resistance, which presents a substantial risk to the health of both farmed shrimp, human and environment. The administration of antibiotics exerts selective pressure that facilitates the proliferation of resistant bacteria, complicating infection control and increasing the risk of transmitting resistant strains to humans via the food chain. The application of antibiotics in aquaculture may result in environmental pollution, as residues from these substances might infiltrate adjacent water bodies, adversely affecting non-target beneficial creatures and degrading the local ecosystem [5]. Timely identification of diseases in shrimp aquaculture is essential for controlling outbreaks and reducing losses. Conventional diagnostic tools for shrimp diseases are frequently constrained by limitations in sensitivity, specificity, and speed, and they are unable to identify diseases in asymptomatic or subclinical phases. Conventional diagnostic methods, including microscopy, culture techniques, and serological assays, are laborious, costly, and necessitate specialized apparatus. These constraints hinder farmers from detecting initial stage infections, permitting pathogens to proliferate uncontrollably prior to the implementation of appropriate interventions. Disease management strategies in shrimp aquaculture frequently require the application of chemicals, antibiotics, and pesticides to regulate pathogens and avert disease dissemination. There are substantial environmental costs associated with these methods, inspite of their effectiveness [6]. Adequate biosecurity is crucial for averting the introduction and dissemination of pathogens in shrimp aquaculture. Shrimp farms frequently have difficulties in executing thorough biosecurity protocols owing to the complexities of regulating water quality, managing farm inputs (including feed and seed stock), and mitigating the invasion of pathogens from external sources. Since shrimp are mainly dependent on innate immunity as it lacks adaptive immunity and have an open circulatory system, it is challenging to use conventional vaccine techniques to target particular infections [7]. Consequently, shrimp producers frequently must depend on chemical treatments and prophylactic antibiotics to reduce the risk of diseases, which exacerbates the overuse of chemicals and the potential for resistance. Farm profitability may be impacted by the rapidly mounting costs of acquiring antibiotics, chemicals, vaccines, diagnostic equipment, and setting biosecurity measures. Furthermore, the economic demands within the sector frequently result in a dependence on short-term remedies, such as the excessive utilization of antibiotics, instead of enduring, sustainable procedures. These difficulties

highlight the pressing necessity for more efficient, sustainable, and eco-friendly strategies to address illnesses in shrimp aquaculture.

Nanotechnology Dependent Disease Management

In recent times, the worldwide aquaculture sector has encountered mounting pressure to diminish dependence on antibiotics for disease management, particularly in shrimp cultivation [8]. Nanotechnology offers a viable avenue for antibiotic-free disease management in shrimp aquaculture. Integrating nanoparticles into shrimp care for disease prevention, water purification, targeted medicinal delivery, and immunity enhancement, enables the industry to adopt more sustainable and environment friendly procedures. Nanotechnology diminishes dependence on antibiotics while promoting healthier shrimp populations and fostering environmentally sustainable aquaculture techniques [9].

Nanosensors

Although molecular-based methods are more sensitive in detecting pathogens, they require expensive and specialized equipment. A consistent demand exists for technologies that are user-friendly, sensitive, rapid, reliable, and specific for field application in order to forecast outbreaks in aquaculture. Providing an efficient yet user-friendly method for pathogen identification, biosensors are capable of onsite and real-time monitoring. Biosensors are analytical instruments that transform biological information into detectable signals, including electrical, magnetic, thermal, electrochemical, or optical. The target analytes of viral RNA or bacterial cells are captured by affixing DNA probes or antibodies to the sensor surface in a conventional biosensor design [10]. The sensitivity and selectivity of the nanosensors are enhanced by the capacity to functionalize nanomaterials with additional biological recognition elements, which is facilitated by the large surface-to-volume ratio and the abundance of surface groups on nanomaterials. The analytical performance of nanosensors is further enhanced by the distinctive characteristics of nano materials. Nanotechnologies and nanomaterials have been enormously employed recently to improve the reactivity and specificity of biosensors for the detection of contaminants or pathogens at the nanoscale. Surface-enhanced Raman spectroscopy (SERS) employing metal nanoparticles imparts distinctive perspectives for identifying infections or toxins in trace amounts [11]. Aptasensors employing DNA nanostructure-modified magnetic beads have been created, in which bacteria compete with the aptameric DNA for attachment to the magnetic beads embedded with DNA, leading to the disintegration of the DNA nanostructures on the bead. The fluctuation in charge or the DNA content on the magnetic beads is measured chronopotentiometrically with a solid-contact electrode that is sensitive to multivalent cations [12].

Antimicrobial Agents

Nanoparticles serve as effective antibacterial agents. The chemical and physical properties of nanoparticles with antibacterial properties vary significantly. Some use "nano-carriers," which are organic-based liposomes and capsules containing either new RNAs or conventional antibiotics, while others use the cations discharged from the surfaces of metal colloids as the primary antibacterial agent [9]. Nanoparticles with antimicrobial properties can be engineered in a safe and efficient manner if the antimicrobial efficacy of each attribute can be quantified, and all of these features are aggregated into a nanoparticle profile. The application of nanoparticles in antimicrobial therapies presents a viable solution to the challenges posed by traditional antibiotic treatments, such as antibiotic resistance and restricted drug absorption. Current research focuses on enhancing nanoparticle design and delivery methods to achieve better antimicrobial results. The increased surface area of nanoparticles significantly contributes to their improved antimicrobial efficacy. The increased drug loading capacity, superior interactions with bacterial cells, and greater contact points are all facilitated by the enhanced surface area of nanoparticles. Nanoparticles demonstrate antimicrobial mechanisms, via the generation of reactive oxygen species, peroxidation of membrane lipids, disruption of ion transport, release of excessive ions, DNA damage, inhibition of protein-protein and protein-DNA interactions, prevention of biofilm formation, and suppression of motility [13].

Metal colloids can be meticulously designed to incorporate various chemical constituents (such as copper or silver) and surface modifications (such as stabilizers for surface charges or aqueous suspension), with a diameter less than 15 nm to enable their permeation through the cell walls of bacteria and other intracellular membranes, or exceeding 50 nm to extend leaching of cations in biological or environmental matrices [14]. Metal oxide nanoparticles consisting of metal and oxygen atoms, are synthesized from a variety of metal elements, including transition metals like iron, titanium, and copper, as well as non-metals such as aluminium and silicon. Compared to their bulk metal oxide counterparts, these nanoparticles exhibit distinctive chemical and physical characteristics owing to their small size and high surface area. Metal nanoparticles consist of nanoscale particles that are primarily made up of metal atoms or metal compounds. These nanoparticles generally possess diameters ranging from 1 to 100 nanometers (nm), corresponding to tens to hundreds of atoms in scale. Silver, copper and zinc are extensively researched and utilized in antimicrobial nanotechnology [15], [16]. The fabrication of biologically active nanoparticles (NPs) using green synthesis techniques has garnered a lot of attention because of its eco-friendly and sustainable properties. These methodologies exploit the resources available naturally while mitigating damage afflicted on the environment. These green synthesis methodologies present advantageous substitutes to conventional techniques. The fundamental procedures and principles of biogenic

nanoparticle production involve stabilization and reduction, wherein biological agents like plant extracts, fungal macromolecules, bacteria, and algae serve as capping and reducing agents that reduce metal ions into nanoparticles [17]. Metal ions coalesce during nucleation, forming tiny clusters that then develop into bigger nanoparticles. The morphology and dimensions of the nanoparticles are dependent upon the biomolecules engaged and the reaction parameters. Nanoparticles of carbon origin are nanometer-scale entities predominantly constituted of carbon atoms, existing in diverse shapes and configurations. These nanoparticles have acquired significant interest owing to their distinctive characteristics and multifaceted applicability across numerous domains. These groups can engage with microbial cells, modifying permeability of membrane and affecting biological functions [18].

Nanoparticles can be administered to shrimp by including them into the diet or by dispersing them in the raising water. These represent the prevalent methodologies for nanomaterial application; nonetheless, recent developments have emerged. In a study, silver nanoparticles (AgNPs) has been attached onto silica beads within a water filtration column, effectively eliminating luminous *Vibrio* sp. Filtered saltwater utilized for the cultivation of post-larval *P. vannamei* enhanced both their survival rate and growth performance [19]. Some key studies on the antimicrobial efficiency of nanoparticles against shrimp pathogens are discussed in Table 1.

Table 1: List of Nanoparticles with Antimicrobial Efficacies against Shrimp Pathogens

Srl No	Pathogen	Nanoparticle	Method of Production	Reference
1.	<i>Vibrio harveyi</i>	AgNP	Biologically manufactured (<i>C. sinensis</i> , <i>P. chilensis</i>), Commercially manufactured (Nanocoid)	[15] [20] [21]
2.	<i>V. parahaemolyticus</i>	AgNP	Green sythesis (<i>Spirulina</i> , <i>U. clathrate</i> , <i>R. hymenosepalus</i> , <i>P. chilensis</i> , <i>G. acerosa</i> , <i>Larrea tridentata</i>)	[22] [23] [24][25][26]
		Ag/AgCl NPs	Green synthesis (<i>Ulva clathrate</i>)	[23]
		AuNP	Chemically manufactured (Turkevich	[27] [28]

			method) Green synthesis (<i>Marphysa moribidii</i>)	
		DAO/DEX-CNGs	Chemically manufactured (One Step)	[29]
		CuNP	Chemically manufactured (One-step method)	[30]
		SeNP	Green synthesis (<i>Sargassum swartzii</i>)	[16]
		ZnO	Green synthesis (<i>Sargassum swartzii</i>)	
		CuO	Green synthesis (<i>Sargassum swartzii</i>)	
3.	<i>V. vulnificus</i>	AgNP	Green syntheis(<i>G. acerosa</i>)	[25]
4.	<i>V. alginolyticus</i>	CuNP	Chemically manufactured (One-step method)	[30]
5.	White Spot Syndrome Virus	AgNP	Commercially manufactured (Argovit)	[31]
		polyamine CQDs	Dry heating treatment	[32]
6.	Necrotizing hepatopancreatitis bacterium (NHP-B)	AgNP	Green syntheis (<i>Azadirachta indica</i>)	[33]
		Chitosan NP	Physicochemically manufactured (Ultrafine milling method)	[34]
7.	<i>A. hydrophila</i>	CuNP	Chemically manufactured (One-step method)	[30]

Nanoparticles for Controlled Delivery of Antimicrobials

A significant problem of antibiotic therapy in aquaculture practices is that antibiotics can impact the entire microbial community within the aquatic environment.

This may result in the disturbance of beneficial microorganisms that preserve water quality. Nanotechnology offers a solution by facilitating the creation of nano-sized drug delivery devices that can target antimicrobials directly to infected regions on shrimp, hence reducing environmental effect and circumventing the systemic application of antibiotics. Nanoparticles have garnered attention as drug delivery systems due to their capacity to traverse biological barriers, attributed to their diminutive size, and their interactive potential, stemming from their substantial surface area to volume ratio, which enables interaction with a greater number of conjugates and compounds. Several bioactive substances have been encapsulated and delivered via encapsulations fabricated from nanoparticles in order to treat and prevent diseases in aquaculture. This approach is favoured due to its safety, biocompatibility, biodegradability, and its ability to confer stability and specificity in drug delivery while minimizing or eliminating side effects [33]. RNA interference (RNAi) has been employed to combat white spot disease of shrimps caused by the white spot syndrome virus (WSSV), through the application of double-stranded RNA (dsRNA) to degrade viral mRNA. Since nucleic acid therapies are vulnerable to environmental variations, it is essential to identify the optimal delivery pathway so that these therapies effectively reach their target cells while preserving stability and functionality. A study extracted chitosan nanoparticles (CNs) from α -chitosan derived from shrimp for the encapsulation of antiviral double-stranded RNA (dsRNA) for oral delivery via shrimp feed. CNs showed stable zeta potential (>20 mV), tiny diameters (<300 nm), and strong encapsulation efficiency ($>95\%$). These CNs demonstrated enhanced RNase protection and controlled release, maintained stability for over a month, provided significant dsRNA stability ($>70\%$), and enhanced protection against WSSV, leading to a notable reduction in mortality [34]. Ag-decorated TiO₂ nanoparticles loaded with doxycycline antibiotic have been shown to significantly protect whiteleg shrimps against AHPND in a study. By lowering the antibiotic concentration, this nano drug delivery method improved treatment efficacy while reducing shrimp antibacterial resistance [35].

Immune Modulation and Stimulation

Certain nanoparticles, in addition to their direct antibacterial actions, demonstrate immune-modulatory capabilities by modulating expression of genes that boost shrimps' innate defense mechanisms against infections generating early immune responses in hemocytes linked to the Toll-like receptor (TLR3) pathway and effector (proPO) [36]. Chitosan nanoparticles loaded with curcumin (Cur-CSNPs) substantially enhanced the relative mRNA expressions of lysozyme, lectin and cMnSOD in shrimps challenged with *Vibrio harveyi*. These immunological activations diminish dependence on antibiotics and enhance the general health and resilience of the shrimp population [36].

Water Quality Maintenance

Maintaining water quality is essential for the success of aquaculture operations. It affects nearly all facets of farming, including the health and growth of cultivated species, environmental sustainability, and economic viability. Aquaculture farms can enhance productivity and minimize their environmental impact by maintaining water parameters within optimal ranges and effectively managing contaminants, thereby fostering healthy, disease-free environments for aquatic organisms. Utilizing nanoparticles and nanomaterials enables aquaculture farms to improve water purification through contaminant removal and decrease the likelihood of disease outbreaks, thereby enhancing the health of both farmed species and the surrounding environment.

Nanofiltration

As demand for shellfish increased, an intensification of farming practices occurred for higher yields. This intensification resulted in nutrient pollution and poor water quality due to increased stocking densities. Elevated population density and suboptimal water quality significantly increase the likelihood of disease outbreaks. Higher disease rates in intensive farming lead to a reliance on antibiotics. Maintaining water quality in shrimp culture is essential for shrimp survival and the health of aquatic life. Nanofiltration effectively removes contaminants from aquaculture farm water, maintaining optimal water quality for the health and growth of farmed species. It plays a crucial role in water reuse through recirculating aquaculture systems (RAS) by effectively eliminating pathogens, pharmaceuticals, waste products such as urea and ammonia, as well as other contaminants of emerging concern (CECs). This process enhances biosecurity, minimizes chemical usage, and promotes sustainability in aquaculture operations. Nanofiltration (NF) is a process driven by pressure where a solvent, is traversed across a selectively permeable membrane by creating hydraulic gradient between the side of the feed and the side of the permeant. The utilization of membranes having either small compact or actively functional pores smaller than 2 nm, distinguishes NF from ultrafiltration as well microfiltration. This characteristic enables the removal of small organic molecules and polyvalent ions [37].

Numerous recent research indicates that the application of nanofilters resulted in over 90% elimination of antibiotics from aquaculture, wastewater, and various aquatic habitats. A study demonstrated that activated carbon (AC) nanoparticles were consistently integrated into the interstitial sites of a thick graphene oxide (GO) membrane, resulting in the creation of numerous small pores (3–10 nm). These pores functioned as conduits for fluid movement, while the carbon and functional groups on the GO surface absorbed 99% of Tetracycline. The GO/AC membrane demonstrates the highest adsorption efficiency among the materials examined, which include pure GO, AC, carbon nanotubes (CNT), and the CNT/AC and GO/CNT hybrids [38].

NF membranes made up of Polyelectrolyte multilayers which are fabricated through the assemblage of a cationic polymer, specifically poly(diallyl dimethylammonium chloride), and an anionic polymer, namely poly(sodium styrenesulfonate), have displayed the capability to reject over 90% of Sulphamethoxazole [39]. The NF 90 (Dow/FilmTec) membrane has demonstrated a removal efficiency exceeding 90% for Sulfamethoxazole and 95% for Trimethoprim [40].

Nanocatalyst Mediated Oxidation

Antibiotic contamination in aquaculture and aquatic ecosystems, along with other organic pollutants, can be mitigated through degradation by oxidation to less toxic metabolites. Ozone-assisted catalysis and photocatalysis mediated degradation represent the principal alternative pathways for the oxidation process catalyzed by nanocatalysts. Nanomaterials serve as optimal catalysts in these processes due to their extensive surface area, ease of modification, increased reactivity of surfaces, and improved mass transfer, all of which collectively enhance overall reaction kinetics. Various photocatalytic graphene oxide (GO) membrane innovations have been facilitated by the synergistic relationship between GO and photocatalytic materials such as TiO₂, as well as due to the efficacy of graphene oxide (GO) membranes with respect to water permeability and CEC rejection. These concepts are capable of simultaneously retaining organics, degrading CECs, and mitigating fouling [41].

A nanocomposite photocatalytic nanofiltration membrane including graphitic carbon nitride (g-C₃N₄), carbon nanotubes (CNTs), TiO₂ nanoparticles and GO was employed to treat actual aquaculture wastewater. In order to enhance the mechanical strength of the GO structure and to facilitate the transport of water across the membrane, CNTs are employed. The photocatalytically active nanoparticle g-C₃N₄/TiO₂ simultaneously improve hydrophilicity of membrane and decompose trapped organic compounds. Furthermore, exposure to ultraviolet light can regenerate the fouled membrane and restore the permeate flow. Despite the fact that the functional membrane exhibited significant retention of organic molecules and dispersed solids under dark conditions, it exhibited remarkable efficacy in terms of dissolved nitrogen species (e.g. ammonia) reduction and water productivity when the photocatalytic nanoparticles were activated with light [42]. In another study, researchers utilized the anodization method to fabricate well-defined nanotube arrays made of TiO₂ (TNAs) and nanowires on nanotube arrays (TNWs/TNAs). The inner tube of TNAs exhibited a diameter of approximately 95 nm and a thickness of around 25 nm. The TNWs/TNAs were partially covered by a layer of TiO₂ nanowires with a length of approximately 6 μ m. These TNAs and TNWs/TNAs demonstrated efficient and rapid degradation of antibiotics Doxycycline, Lincomycin, Oxytetracycline, Sulfamethoxazole, Sulfamethazine under UV-VIS irradiation at 120 mW/cm², achieving over 95% removal within 20 minutes [43].

Application of Nanotechnology in Shrimp Culture

The long-term sustainability and growth of aquaculture practices like shrimp farming are undoubtedly significantly influenced by nanotechnology [44]. To date, numerous nanotechnology-oriented solutions have been demonstrated to improve the primary facets of aquaculture practices. Nevertheless, the technology is still in its infancy. The toxicity of nanoparticles is a subject of increasing concern in this field. The potential toxicity of nanoparticles to shrimp and the broader aquatic ecosystem is a valid concern that has been raised by their introduction into aquaculture [45]. The toxicity of nanoparticles varies significantly based on factors like size, shape, and chemical composition. Certain nanoparticles have shown different levels of toxicity in laboratory environments, underscoring the importance of thorough toxicity evaluations prior to their widespread use. Long-term studies investigating the chronic effects of nanoparticle exposure on shrimp are essential for ensuring responsible and safe implementation [46]. The possibility of nanoparticles accumulating in shrimp tissues and then biomagnifying through the food chain poses a considerable challenge. The bioaccumulation of contaminants in shrimp presents significant risks to human health associated with their consumption. Therefore, it is necessary to undertake comprehensive research to evaluate the potential dangers to consumers by examining the bioaccumulation potential of various nanoparticles in shrimp and the entire food web. Currently, the manufacturing procedure and application of nanoparticles can be costly, which may impede their widespread adoption in shrimp aquaculture [45]. Substantial technological advancements and substantial cost reductions are necessary to scale up nanoparticle production to satiate the demands of broad-scale shrimp farming. Economical and efficient production methods are essential for the successful transition of nanoparticle technology from laboratory settings to commercial applications. The absence of distinct regulatory frameworks for the application of nanoparticles in aquaculture creates uncertainty for both farmers and researchers. The adoption of nanoparticle-based solutions in shrimp farming can also be substantially influenced by the public perception of nanotechnology in food production. To establish public trust and guarantee the successful integration of this technology, it is essential to cultivate transparent communication about the benefits and risks associated with nanoparticle use and establish robust frameworks for its regulation. Although nanoparticles hold great promise for managing shrimp diseases, a considerable knowledge gap persists concerning their long-term impacts on shrimp health and the environment. Additional research is essential to assess the efficacy, safety, and environmental effects of different nanoparticle types in various farm settings.

Conclusion

Nanoparticles present significant opportunities for transforming the management of shrimp diseases and advancing sustainable practices in aquaculture.

Nonetheless, recognizing this potential requires an integrated strategy that both acknowledges and proactively tackles the challenges linked to toxicity, bioaccumulation, cost, and regulatory frameworks. By engaging in thorough research, fostering responsible development, and maintaining transparent communication, we can effectively leverage the benefits of nanotechnology to improve shrimp health, promote environmental sustainability, and guarantee the continued viability of the shrimp farming sector. The trajectory of sustainable shrimp aquaculture relies on a careful yet progressive approach with nanoparticle technology, emphasizing the dual focus on its advantages and the management of possible risks.

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Synthesis and Gas Sensing Application of Zinc Oxide Nanoflowers – A Short Review

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Abstract

Nanosized zinc oxide (ZnO) with a flower-like morphology have received paramount attention due to its striking physico-chemical properties attributed to its distinguished morphology and large surface area which makes it a suitable candidate for diverse technological application. This review deals with different synthesis techniques, characterization tools and gas sensing capability of ZnO flower-like nanostructures. The review on existing study suggests that the self-assembled hierarchical architectural structure of ZnO displays improved gas detection sensitivity and selectivity towards sensing of different gases like SO₂, NO₂, CO, H₂ and other volatile organic chemicals.

Keywords: Zinc Oxide, Nanoflower, Gas Sensing, Morphology.

Introduction

Nanosized zinc oxide (ZnO) is a versatile multifunctional compound which exhibits remarkable physicochemical properties due to which it has been successfully utilized in diverse technological sectors like electronic and optoelectronic devices, environmental remediation through photocatalytic degradation of toxic dyes, removal of heavy metals from waste water, biomedical fields etc. [1-5]. ZnO is low cost, non-toxic and biocompatible in nature and can be easily synthesized in various morphological forms like nanoparticle, nanorod, nanowire, nanocube, nanosphere,

nanoflowers etc. which can display exceptional optical, electronic, catalytic properties and can be beneficially utilized in solar cells, energy storage devices, LED and other optoelectronic devices, drug delivery system and other different sectors [6 – 8]. ZnO possesses hexagonal wurtzite crystal structure with $P6_3mc$ space group [9]. ZnO has a wide direct bandgap (~ 3.37 eV) for which it is considered as an efficient material for application in electronic, optoelectronic devices [10]. Intrinsically, zinc oxide is an n-type semiconducting material due to presence of oxygen vacancy in the crystal lattice and zinc interstitial defects at the tetrahedral and octahedral sites [11]. Nanometric ZnO exhibits appreciable UV and visible region luminescence making it important for optical applications [12]. In addition to the striking optical and electrical properties, ZnO exhibits good thermal, mechanical and chemical stability and biocompatibility [8]. It has been well established that by synthesizing different types of nanostructures of ZnO, one can easily tune its structural, electrical, optical, chemical properties through modification of shape and size of the system [8]. At nano regime, ZnO exhibits high surface to volume ratio, unique crystal defects along with quantum confinement effects which improves its physico-chemical properties and makes them suitable for technological application [13, 14]. ZnO nanorod exhibits high surface area and aspect ratio which make them ideal for application in catalysis, biosensing, LED and other optoelectronic devices [15]. On the other hand, ZnO nanospheres have high surface area which enhance their catalytic activity and makes them useful in biomedical application [16]. Therefore, synthesis of different morphological forms of 1D and 2D nanostructures helps to tune optical, electrical, chemical properties of ZnO which allow researchers to explore and optimize its potential for specific industrial, environmental, and biomedical applications. In this context, the synthesis and study of physicochemical properties of ZnO nanoflower-like structures is important because the unique morphological form having high surface area in addition to the exceptional interconnected nanostructures markedly enhance their functionality [17]. The petal-like porous hierarchical structure of ZnO nanoflowers have large surface to volume ratio and increased number of active sites which markedly improve their catalytic, gas sensing and SERS sensing property [17, 18]. In addition, the porous hierarchical nanoflower like structures of ZnO exhibits rapid charge transport, enhanced light scattering and light absorption properties which are crucial for their application in solar cell, photodetectors, energy storage devices and optoelectronic devices [17, 19]. In biomedical field, ZnO nanoflowers have been utilized in biosensing, diagnostic tools, therapeutic and antimicrobial agent and other sectors [17]. Researchers can gain a deeper understanding of the interaction between structure and different physicochemical properties by investigating ZnO nanoflowers, which opens up new opportunities in energy, environmental, and healthcare technology. In this short review different synthesis route of nanoflower like structures of ZnO and their application in gas sensing have been discussed.

Synthesis Techniques of ZnO Nanoflower

There are several conventional techniques for the synthesis of ZnO nanoflowers. Among these, hydrothermal method is the most common technique which is a low cost solution based approach performed at comparatively low temperature [20]. Taheri et al. reported the synthesis of flower like ZnO nano structures by solgel electrophoretic deposition technique by using diethanolamine as stabilizer [21]. Ling-Min et al. reported the synthesis of ZnO nanoflowers by a two step sol-gel method with varied concentration of seed and growth solution [22]. N. Zhang et al. have synthesized rose like nanoflower structures of ZnO through novel chemical vapor deposition method [23]. A. Das et al. synthesized marigold flower-like (~ 28.46 nm) and rose like (~ 28.07 nm) ZnO structures by hydrothermal and microwave assisted hydrothermal methods, respectively [19]. A. K. Zak et al. have reported the synthesis ZnO nanoflowers by a facile and fast sonochemical method through variation of sonication time [24]. A. F. Abdulrahman used spray pyrolysis synthesis technique which is a scalable and comparatively easy and low cost technique for the synthesis of ZnO nanoflowers [25]. V. K. Mohan et al. have reported the synthesis of ZnO nanoflower by a simple pH controlled coprecipitation technique [26]. Rajukumar C. adopted coprecipitation synthesis technique using diethanolamine with polyethylene glycol to synthesize flower like morphology of ZnO [27]. Recently, biosynthesis of nanomaterials have attracted paramount attention due to its benign nature and biocompatibility [28]. J. A. Mazumder et al. have synthesized ZnO nanoflowers by using enzyme α -amylase as a biomimetic agent [28]. A. S. Rini et al. proposed a green synthesis method for synthesizing ZnO nanoflower using pineapple peel extract with variation of zinc precursor [29]. R. M. Tripathi et al. have reported an efficient bio synthesis technique using thermophilic non-pathogenic bacteria of ZnO nanoflower [30]. O. Smirnov et al. have synthesized flower type ZnO nanoparticles by a colloidal route using a fungi as a reducing agent [31]. Choice of a proper synthesis method of nanomaterial is essential as it can tune the shape and size of the sample which in turn plays the crucial role to optimize their applicability in diverse technological fields.

Characterization Techniques

Systematic characterization of ZnO nanoflower is of utmost importance to study their structural, microstructural, morphological, electrical, chemical and optical properties. Powder x-ray diffraction is the most elementary structural characterization technique. Through Rietveld refinement of the x-ray diffraction data we can get clear insight into the structural and microstructural property of the system through estimation of crystallite size, lattice strain, phase purity of the sample [32]. Fourier transform infrared spectroscopic technique (FTIR) can provide information on chemical bonding, surface modification by functional group through identification of vibrational modes of different chemical bonding [30]. Raman spectroscopy can also

provide important structural information on lattice vibration, chemical bonding, defects and crystalline quality of the sample [33]. The flower like morphology of ZnO nanoparticle system can be easily investigated by Scanning electron microscopy (SEM) and deeper insight into the microstructural character of the sample along with information on lattice fringes can be obtained by using transmission electron microscopic (TEM) technique [8, 19]. Optical Property of ZnO nanoflowers can be investigated by UV-Vis and photoluminescence spectroscopic techniques [31]. Elemental chemical composition and valence state of the constituting elements can be estimated by using energy dispersive x-ray spectroscopy (EDS) and x-ray photoelectron spectroscopy (XPS) [32].

Some Application of ZnO Nanoflowers in Gas Sensing

ZnO nanoflowers (~ 60 nm) synthesized by S. Zhang et al. through thermal decomposition method have been successfully utilized for hazardous acetone gas sensing and presence of ample amount of oxygen vacancy in between the junctions of the petals of the nanoflower structure markedly improved the sensing ability [34]. S. Agarwal et al. have synthesized hierarchically organized ZnO nanoflowers comprising of ZnO nanoparticles by hydrothermal method and they also have reported gas sensing property of their sample towards benzene, ethanol, CO and NO₂ along with they have proposed that nanoflower like structure is more efficient sensor due to large surface and defects [35]. R. S. Ganesh et al. reported the hydrothermal synthesis of three dimensional structures of ZnO and their promising role in ammonia (NH₃) gas sensing [36]. J-W Kim et al. have synthesized novel double faced ZnO nanoflowers which showed excellent sensing capacity of NO₂ [37]. Simple solution method derived ZnO nanoflowers have been used by A. Umar et al. to fabricate low cost electrode material for efficient detection of H₂S [38]. Zhou et al. reported the efficient SO₂ gas sensing ability of ZnO nanoflowers synthesized by hydrothermal method [39]. P. Tiwary et al. have prepared flower type structures of ZnO and described their high sensitivity towards sensing of ammonia (NH₃) and volatile methanol and ethanol [40]. Chen et al. proposed a two-step hydrothermal synthesis method using H₂ treatment for the synthesis of zinc oxide nanoflowers having high defects for rapid detection of methane (CH₄) at low concentration [41].

Conclusion

The above short review suggest that nanoflower-like structures of zinc oxide is a useful material for gas sensing applications due to their unique morphology. These structures have high surface-to-volume ratio along with abundance of active sites which markedly improve gas adsorption as well as detection capability of the system and ZnO nanoflowers have shown excellent sensitivity and selectivity towards NO₂, SO₂, CO, H₂S, methane, ammonia and other various gas sensing. The gas sensing efficiency of ZnO have been found to be strongly dependent upon size, shape,

crystalline character along with order of defect of the structure and different research groups are involved in research to enhance and optimize the use of ZnO nanostructure in gas sensing through tuning their properties and forming nanocomposites with efficient materials.

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Reductive Thiocyanolysis of Tetraoxorhenate (VII): Synthesis, Crystal Structure, Catalytic Oxidation and Kinetic Studies

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Abstract

This study investigates the reductive thiocyanolysis of tetraoxorhenate (VII), focusing on the synthesis of novel rhenium-thiocyanate complexes, their structural characterization, catalytic oxidation properties, and kinetic behaviour. The resulting rhenium complexes were synthesized and characterized through spectroscopic and crystallographic methods. The catalytic performance of these complexes was evaluated in oxidative reactions, with a detailed kinetic study to understand the reaction mechanism. This paper offers insights into the reactivity of rhenium compounds with thiocyanate, expanding their potential use in catalysis and inorganic synthesis.

Keywords: Single-Crystal X-ray Diffractometer, Catalytic Activity, Reductive Thiocyanolysis.

Introduction

Rhenium compounds, particularly those with high oxidation states, have attracted attention in the field of catalysis due to their stability and versatile oxidation properties. Tetraoxorhenate (VII) ions ($[\text{ReO}_4]^-$) are known for their high oxidation potential, making them promising candidates for catalytic and oxidative applications. The reaction between $[\text{ReO}_4]^-$ and thiocyanate ions (SCN^-) represents a reductive

thiocyanolysis process, where the thiocyanate ion acts as a reductant, converting Re(VII) to a lower oxidation state and forming novel rhenium-thiocyanate complexes.^[1]

This study explores the synthesis, crystal structure, catalytic oxidation activity, and kinetics of rhenium-thiocyanate complexes formed through reductive thiocyanolysis of tetraoxorhenate (VII). Understanding these parameters can shed light on the complexation behaviour of high-valent rhenium species and their potential catalytic applications in oxidation reactions.

Experimental Section

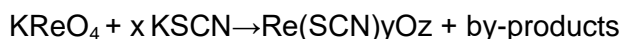
Materials and Methods

All chemicals, including potassium perrhenate (KReO_4) and potassium thiocyanate (KSCN), were purchased from commercial sources and used without further purification. Deionized water and analytical-grade solvents were employed in all procedures.

Synthesis of Rhenium-Thiocyanate Complexes

In a typical synthesis, an aqueous solution of KReO_4 was reacted with an excess of KSCN in acidic or neutral conditions. The mixture was stirred under controlled temperature and pH conditions, leading to the formation of a precipitate. The precipitate was filtered, washed, and dried in a vacuum desiccator. The reaction conditions, including molar ratios, temperature, and pH, were systematically varied to optimize the yield and purity of the rhenium-thiocyanate complex.^[2]

The generalized reaction can be represented as:



Where x , y , and z are determined based on reaction conditions.

Crystallization and Crystal Structure Determination

Single crystals suitable for X-ray crystallography were obtained through slow evaporation of the complex solution at room temperature. The crystal structure was determined by X-ray diffraction using a single-crystal X-ray diffractometer. Structural parameters, including bond lengths, angles, and coordination geometry, were analyzed to elucidate the molecular structure.

Catalytic Oxidation Studies

The catalytic activity of the synthesized rhenium-thiocyanate complex was tested in the oxidation of organic substrates, such as alkenes or alcohols, using an oxygen donor (e.g., H_2O_2) in an organic solvent. Reaction conditions, including catalyst loading, temperature, and substrate concentration, were optimized to maximize conversion and selectivity.^[3]

Kinetic Studies

The kinetics of the reductive thiocyanolysis of $[\text{ReO}_4]^-$ and the catalytic oxidation reactions were monitored using UV-Vis spectroscopy. Reaction rates were measured under various concentrations of reactants, and the data were fitted to kinetic models to determine reaction order and activation parameters.

Results and Discussion

Synthesis and Yield Optimization

The reductive thiocyanolysis process yielded rhenium-thiocyanate complexes with variable oxidation states depending on reaction conditions. Higher yields were achieved under acidic conditions, likely due to enhanced reduction potential of $[\text{ReO}_4]^-$.

Crystal Structure Analysis

X-ray crystallography revealed that the rhenium-thiocyanate complex exhibited a distorted octahedral geometry around the rhenium center. Each rhenium atom was coordinated to oxygen and thiocyanate ligands, with Re-O and Re-SCN bond distances characteristic of mixed-ligand rhenium complexes. The structural data provided insights into ligand arrangement and coordination, indicating that thiocyanate ligands primarily occupy equatorial positions around the metal center.

Catalytic Oxidation of Organic Substrates

The synthesized rhenium-thiocyanate complex exhibited promising catalytic activity in the oxidation of organic substrates. For example, oxidation of cyclohexene to cyclohexene oxide occurred with high selectivity and yield. The rhenium-thiocyanate complex likely acts as a homogeneous catalyst, facilitating electron transfer to the substrate.

- **Reaction Mechanism:** The proposed mechanism involves coordination of the substrate to the rhenium center, followed by oxidation through interaction with an oxygen donor, such as H_2O_2 . Regeneration of the active catalytic species was observed, suggesting a potential catalytic cycle.
- **Kinetic Studies:** The reductive thiocyanolysis reaction followed pseudo-first-order kinetics with respect to $[\text{ReO}_4]^-$, and rate constants were determined across varying thiocyanate concentrations. Arrhenius plots provided activation energy values, highlighting the temperature dependence of the reaction.

For catalytic oxidation, the reaction exhibited a first-order dependence on substrate concentration, and Michaelis-Menten kinetic parameters were calculated. The results indicate that the rhenium-thiocyanate complex operates via a mechanism involving substrate binding and intermediate formation.

Mechanistic Insights

The combination of structural, catalytic, and kinetic data suggests that thiocyanate serves as a reducing agent, enabling the formation of Re(V) or lower oxidation state species. These intermediate rhenium species can then engage in catalytic cycles for oxidative transformations. The mechanistic pathway is proposed as follows:

- **Initial Reduction:** $[\text{ReO}_4]^-$ reacts with SCN^- , reducing the rhenium to a lower oxidation state.
- **Catalytic Cycle Initiation:** The reduced rhenium species coordinates to the substrate, facilitating electron transfer.
- **Oxidation and Product Formation:** An oxygen donor oxidizes the substrate, regenerating the active catalyst.

Conclusions

This study demonstrates the successful synthesis and characterization of rhenium-thiocyanate complexes through the reductive thiocyanolysis of $[\text{ReO}_4]^-$. The crystal structure revealed an octahedral geometry with thiocyanate and oxygen ligands around the rhenium center. The rhenium-thiocyanate complex showed notable catalytic activity in the oxidation of organic substrates, with kinetic data supporting a mechanism involving substrate coordination and oxidation. These findings highlight the potential of rhenium-thiocyanate complexes as effective catalysts for oxidation reactions, expanding their application in synthetic and industrial chemistry.

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A Review on A Green Approach to Boost Agricultural Productivity

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Abstract

Agriculture faces numerous challenges, including soil degradation, pest infestations, climate change, and the need for increased food production to meet global demands. In response to these issues, the application of green technologies, particularly nanotechnology, offers promising solutions. This review explores the role of zinc oxide nanoparticles (ZnO-NPs) as a sustainable and eco-friendly approach to boost agricultural productivity. ZnO-NPs have gained significant attention due to their unique physicochemical properties, such as antimicrobial activity, enhanced nutrient uptake, and their potential to improve soil health and crop growth. The synthesis methods of ZnO-NPs, including chemical, physical, and plant-mediated approaches, are discussed, with a focus on green synthesis routes that avoid toxic chemicals and promote environmental sustainability. This review highlights how ZnO-NPs can enhance seed germination, plant growth, and stress tolerance, while also providing effective solutions for pest and disease control. Furthermore, the environmental impact, potential risks, and strategies to minimize toxicity of ZnO-NPs in agricultural settings are critically examined. Overall, this review emphasizes the potential of ZnO-NPs in advancing sustainable agricultural practices by improving crop productivity, reducing the need for harmful chemicals, and enhancing the overall health of ecosystems. The article also discusses the challenges and future directions for the widespread adoption of ZnO-NPs in agriculture, with a focus on developing safe, efficient, and scalable solutions for the agricultural industry.

Keywords: ZnO NPs, Physical Properties, Optical Properties, Agriculture Applications, Antimicrobial Properties.

Introduction

Nanotechnology is a rapidly advancing field that has the potential to bring about a revolution across various scientific disciplines, including optics, electronics, biomedical sciences, and materials scienceⁱ. In recent years, research in this area has surged, offering innovative solutions to challenges in multiple domains.

Nanotechnology focuses on nanoparticles, which are atomic or molecular aggregates with sizes typically smaller than 100 nm. These particles represent modified forms of basic elements, achieved by altering their atomic and molecular properties^{ii,iii}. Nanoparticles have attracted significant interest due to their unique and remarkable properties, which offer a wide range of applications compared to their bulk counterparts.

Zinc oxide (ZnO) is an inorganic compound with the chemical formula ZnO. It appears as a white powder and is almost insoluble in water. This powder is widely used as an additive in a variety of materials and products, including ceramics, glass, cement, rubber (e.g., car tires), lubricants, paints, ointments, adhesives, plastics, sealants, pigments, foods (as a source of zinc), batteries, ferrites, and fire retardants. While ZnO naturally occurs as the mineral zincite in the Earth's crust, most of the ZnO used for commercial purposes is produced synthetically. In materials science, ZnO is referred to as a II-VI semiconductor because zinc and oxygen belong to the 2nd and 6th groups of the periodic table. The ZnO semiconductor possesses several unique properties, such as excellent transparency, high electron mobility, a wide band gap, and strong luminescence at room temperature. These characteristics make it useful in applications such as transparent electrodes in liquid crystal displays, energy-saving or heat-protecting windows, and other electronic devices. Zinc oxide (in its wurtzite structure, p63m) is a wide band gap semiconductor with an energy band gap of 3.3 eV at room temperature (RT).

The distinctive properties of nanomaterials have inspired researchers to develop simpler and cost-effective methods for producing nanostructures of important technological materials. Among various metal oxide nanoparticles, zinc oxide is considered one of the most widely studied and utilized at the nanoscale. Its wide band gap and large excitonic binding energy have made ZnO significant for both scientific research and industrial applications^{iv}. Crystalline ZnO has a wurtzite (B4) crystal structure, characterized by a hexagonal unit cell with two lattice parameters, a and c . In this wurtzite structure, each anion is surrounded by four cations located at the corners of a tetrahedron, which demonstrates tetrahedral coordination and leads to sp^3 covalent bonding. The tetrahedral arrangement of ZnO results in a non-centrosymmetric structure, shown in figure 1.

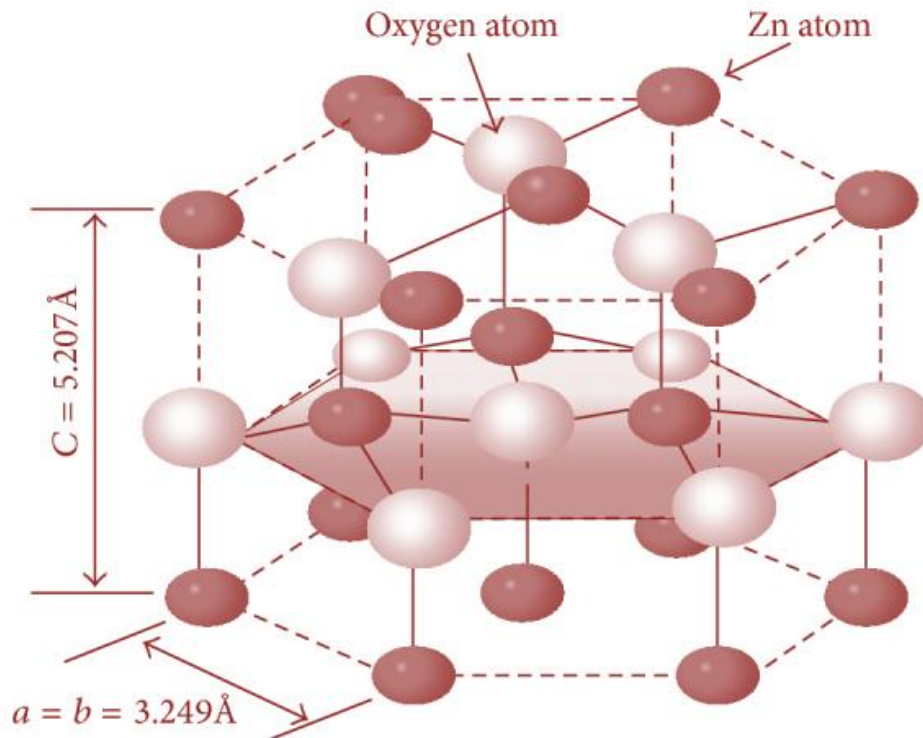


Fig 1: Tetrahedral structure of ZnO

Physical Properties of ZnO NPs

Zinc oxide nanoparticles possess remarkable physical properties. It is important to note that as the dimensions of semiconductor materials are reduced to the nanometer scale, some of their physical properties change due to what is known as the "quantum size effect." For instance, quantum confinement leads to an increase in the band gap energy of quasi-one-dimensional (Q1D) ZnO, a phenomenon that has been confirmed through photoluminescence studies.

Optical Properties of ZnO Nanoparticles

The intrinsic optical properties of ZnO nanostructures are being widely investigated for use in photonic devices. The photoluminescence (PL) spectra of ZnO nanostructures have been extensively documented^v. Photoconductivity measurements of ZnO nanowires reveal that the presence of O_2 plays a significant role in the photoresponse. It was observed that the desorption-adsorption process of O_2 influences the photoresponse of ZnO nanowires. When illuminated, photogenerated holes discharge chemisorbed O_2 on the surface through electron-hole recombination, while photogenerated electrons lead to a significant increase in conductivity. Once the illumination is turned off, O_2 molecules re-adsorb onto the nanowire surface, causing a decrease in conductivity^{vi}.

Antimicrobial Properties of ZnO Nanoparticles

The antimicrobial activities of metal oxide (ZnO NPs) powders against *Staphylococcus aureus*, *Escherichia coli*, and fungi were quantitatively assessed in culture media. It was found that the growth inhibition was significantly greater in biologically synthesized ZnO nanoparticles compared to chemically synthesized ZnO and other common antimicrobial agents. The enhanced bioactivity of these smaller particles is attributed to their higher surface area-to-volume ratio. ZnO nanoparticles prove to be an effective antimicrobial agent against pathogenic microorganisms. The antibacterial activity of these particles is mainly attributed to the active oxygen species generated by the metal oxide.

The antibacterial mechanism of ZnO nanoparticles involves direct interaction with the cell surface, affecting membrane permeability. This allows the nanoparticles to enter the bacterial cells, inducing oxidative stress, which inhibits cell growth and leads to cell death. The demonstrated antibacterial properties of ZnO nanoparticles suggest their potential application in food preservation. They can be used as powerful sanitizing agents to disinfect and sterilize equipment and containers in the food industry, protecting them from contamination by foodborne pathogenic bacteria. Additionally, ZnO nanoparticles show both toxicity to harmful bacteria (e.g., *Escherichia coli* and *Staphylococcus aureus*) and beneficial effects on microbes such as *Pseudomonas putida*, which has bioremediation potential and is a strong root colonizer^{vii}.

Applications and Uses of Zinc Oxide Nanoparticles

Zinc oxide nanoparticles (ZnO NPs) have garnered significant attention due to their unique properties and diverse applications in fields such as transparent electronics, ultraviolet (UV) light emitters, piezoelectric devices, chemical sensors, and spin electronics^{viii}.

ZnO is non-toxic and serves as an effective photocatalyst for the degradation of environmental pollutants. Both bulk and thin films of ZnO exhibit high sensitivity to various toxic gases^{ix}.

Additionally, ZnO is recognized as a "generally recognized as safe (GRAS)" material by the U.S. Food and Drug Administration and is used as a food additive. ZnO nanostructures demonstrate high catalytic efficiency and strong adsorption capacity, making them ideal for applications such as sunscreens. Among various metal oxide nanoparticles, ZnO stands out due to its broad range of applications, including gas sensors, biosensors, cosmetics, data storage, optical devices, window materials for displays, solar cells, and drug delivery systems^x.

Medicinal Applications of ZnO Nanoparticles

ZnO NPs have shown potential in the central nervous system (CNS), possibly influencing neuronal excitability and neurotransmitter release during disease

development. Some studies suggest that ZnO NPs may affect the functions of various cells and tissues, their biocompatibility, and neural tissue engineering^{xi,xii}. However, there is limited information on their impact on CNS diseases. ZnO NPs have been shown to modulate synaptic transmission in vitro and enhance spatial cognition in rats by promoting long-term potentiation (LTP). Exposure to ZnO NPs has also been associated with genotoxic effects, possibly mediated by lipid peroxidation and oxidative stress^{xiii}. Despite these concerns, ZnO NPs have shown promise in targeted treatments for cancer and autoimmune diseases^{xiv}.

Role of ZnO Nanoparticles in Agriculture

Agriculture is a cornerstone of the economies in developing countries, but it faces numerous global challenges, including climate change, urbanization, sustainable resource use, and environmental issues like runoff and the accumulation of pesticides and fertilizers. Additionally, the rapidly growing global population, which is expected to rise from 6 billion to 9 billion by 2050, is intensifying the demand for food. As a result, efficient techniques must be adopted to make agriculture more sustainable [38].

Nanotechnology plays a crucial role in transforming agriculture and food production, offering the potential to revolutionize traditional agricultural practices. A significant issue with agrochemicals applied to crops is that they are often lost and fail to reach their target sites due to factors like leaching, drifting, hydrolysis, photolysis, and microbial degradation. Nanoparticles and nanocapsules provide an effective solution by enabling controlled, targeted delivery of pesticides and fertilizers, thereby reducing collateral damage. The use of nanotechnology in farming is gaining attention for its ability to precisely control the release of pesticides, herbicides, and fertilizers. Additionally, nanosensors can help determine the precise amount of farm inputs needed, such as fertilizers and pesticides. Nanosensors designed for pesticide residue detection are highly sensitive, offer low detection limits, are super-selective, and respond quickly. They can also monitor soil moisture and nutrient levels. Nanofertilizers can be rapidly absorbed by plants, and nanoencapsulated slow-release fertilizers help save on fertilizer consumption while minimizing environmental pollution.

Zinc oxide nanoparticles (ZnO NPs) show promise in enhancing the growth and yield of food crops. For example, peanut seeds treated with different concentrations of ZnO nanoparticles (with an average particle size of 25 nm) at a concentration of 1000 ppm demonstrated improved seed germination, seedling vigor, and overall plant growth. These nanoparticles were also effective in promoting root and stem development in peanuts [39].

ZnO nanoparticles are also used in colloidal form as fertilizers, referred to as nanofertilizers. These nanofertilizers provide nutrients to plants while also helping to

restore soil to an organic state, without the harmful effects associated with traditional chemical fertilizers^{xv}. A major advantage of nanofertilizers is that they can be applied in very small amounts. For instance, an adult tree requires only 40–50 kg of nanofertilizer, compared to 150 kg of conventional fertilizers. Nanopowders are proving to be effective as both fertilizers and pesticides^{xvi}. Research has shown that the yield of wheat plants treated with metal nanoparticles increased by an average of 20–25%.

Impact of ZnO Nanoparticles on Plants

Metal oxide nanoparticles can play a significant role in promoting plant growth and yield. However, as research on the toxicological effects of nanoparticles continues to grow, only a limited number of studies have been conducted to assess the impact of ZnO nanoparticles (ZnO NPs) on plants^{xvii}. A study investigated seed germination and root growth in six plant species (radish, rape, ryegrass, lettuce, corn, and cucumber) and evaluated the toxicity of five types of nanoparticles (multiwalled carbon nanotubes, aluminum, alumina, zinc, and zinc oxide). The findings indicated that seed germination was generally unaffected by most of the nanoparticles, but root elongation was inhibited. The estimated IC₅₀ for ZnO NPs was around 50 mg/L for radish and approximately 20 mg/L for rape and ryegrass.

Toxicological studies on ryegrass revealed that exposure to ZnO NPs resulted in a significant reduction in biomass, with the root tips becoming shrunken. Root epidermal and cortical cells showed signs of vacuolation and collapse. ZnO NPs were primarily found adhered to the surface of the roots, and individual nanoparticles were observed within the apoplast and protoplast of the root endodermis and stele. Very few or no zinc ions were translocated into the ryegrass tissues exposed to ZnO nanoparticles.

Conclusion

Zinc oxide nanoparticles (ZnO-NPs) offer a promising green approach to enhancing agricultural productivity by addressing key challenges such as soil degradation, pest infestations, and the need for sustainable crop management. Their unique properties, including antimicrobial activity, enhanced nutrient uptake, and improved plant growth, make them effective tools in boosting crop yields and promoting soil health. ZnO-NPs have shown significant potential in enhancing seed germination, plant growth, stress tolerance, and pest control, while minimizing the need for harmful chemicals. Green synthesis methods for ZnO-NPs further align with environmental sustainability goals, offering an eco-friendly alternative to traditional agricultural practices. Despite the benefits, careful consideration of potential environmental impacts and toxicity is necessary to ensure their safe and effective use in agriculture. Future research and development should focus on optimizing synthesis methods, reducing toxicity, and scaling up ZnO-NPs for widespread application in sustainable farming practices.

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