Advancing Technology with Multidisciplinary Innovation for *Sustainable Growth*

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PREFACE

Technological advancement has always been the cornerstone of human progress, and in today's rapidly evolving world, it thrives most powerfully through multidisciplinary collaboration. The book "*Advancing Technology with Multidisciplinary Innovation for Sustainable Growth*" embodies this spirit of convergence, uniting diverse research domains to address contemporary challenges and envision future possibilities. Each chapter in this book demonstrates how bridging disciplinary boundaries can unlock transformative potential, driving sustainable development across industries and societies.

The compilation begins with explorations in advanced manufacturing and material sciences, showcasing innovative techniques such as electrochemical micromachining of complex alloys and composites, as well as studies on moisture absorption and thermal behavior of laminates. These investigations reveal how precision engineering and material optimization can enhance performance, durability, and sustainability, setting the foundation for technological growth that respects environmental constraints while pushing industrial capabilities forward.

From there, the discourse moves into the realm of education and human capital, where digital transformation and data-driven systems are reshaping how people learn and work. The transition from traditional classrooms to dynamic e-learning environments and the evolution toward HR 4.0 through Human Resource Information Systems illustrate how technological integration empowers individuals, optimizes workforce potential, and sustains organizational competitiveness in an increasingly knowledge-driven economy.

Emerging research in nanotechnology and bio-based solutions underscores the promise of science-driven sustainability. Chapters highlighting nanocomposites with antimicrobial properties, nano additives for biodiesel enhancement, and algae-based carbon emission control systems exemplify how converging disciplines can create environmentally responsible innovations. These works emphasize that technological advancement must be aligned with ecological stewardship to secure long-term global well-being.

Further, the collection delves into the intersection of safety, energy, and industrial design, with studies on intelligent gas leak detection systems, innovative brake plate engineering, and the conversion of waste plastics into usable oil. These chapters showcase how multidisciplinary thinking can address pressing environmental and safety concerns, transforming risks and waste into opportunities and resources.

The final contributions explore cutting-edge solutions like nanocoatings for mechanical systems and the integration of artificial intelligence into marketing technologies. These advances reflect how intelligent systems and smart materials are revolutionizing industrial applications, expanding functional capabilities, and redefining consumer engagement. Collectively, the chapters affirm that sustainable growth will emerge not from isolated progress, but from the collaborative synergy of diverse scientific and technological disciplines working toward a shared future.

We would like to extend our sincere thanks to our publisher, Scientific Research Reports, Chennai, India, for their dedicated efforts in preparing this book, which provides enriched content.

Wishes and Regards,

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Chapter 1

Experimental Investigation and Comparative Study of Input Parameters of Electrochemical Micromachining Process for Machining Inconel Alloy and Composite Materials

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Abstract

Electrochemical Micromachining (EMM) is an advanced non-traditional machining technique widely applied for producing high-precision micro-features in difficult-to-machine materials. Inconel alloys and composite materials, due to their superior strength, heat resistance, and complex microstructures, pose significant challenges to conventional machining processes. This study experimentally investigates and compares the influence of key input parameters, such as voltage, electrolyte concentration, inter-electrode gap, and pulse frequency, on the machining performance of Inconel alloy and composite materials. A design of experiments (DOE)-based methodology was employed, and responses including material

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removal rate (MRR), surface roughness (Ra), and overcut were analyzed. The results revealed that optimized input parameters enhanced machining efficiency and surface integrity, with noticeable differences in machining behavior between metallic and composite substrates. This research highlights the potential of EMM in delivering high-precision micro-features while minimizing machining defects, providing valuable insights for industrial applications.

Keywords: Electrochemical Micromachining; Inconel Alloy; Composite Materials; Input Parameters; Surface Integrity;

1. Introduction

Electrochemical Micromachining (EMM) has emerged as one of the most advanced non-traditional machining techniques capable of producing high-precision micro-features on hard-to-machine materials. Unlike conventional machining, EMM removes material through controlled anodic dissolution without inducing thermal stresses, residual stresses, or tool wear, which makes it highly suitable for manufacturing intricate features at the micro-scale. With industries such as aerospace, biomedical, automotive, and energy increasingly demanding miniaturized components with high surface integrity, EMM has gained considerable research and industrial importance.

Inconel alloys, particularly Inconel 718, are nickel-based superalloys widely recognized for their superior strength, resistance to oxidation, and ability to retain mechanical properties at elevated temperatures. These characteristics make them ideal for applications in gas turbines, jet engines, and energy systems. However, their high hardness, work-hardening tendency, and poor machinability pose severe challenges in conventional machining processes, often leading to rapid tool wear, surface damage, and low material removal efficiency.

On the other hand, fiber-reinforced composite materials have become increasingly important due to their high strength-to-weight ratio, corrosion resistance, and adaptability for multifunctional engineering applications. They are extensively used in automotive, defense, and biomedical sectors for lightweight structural components. However, composites present their own machining difficulties, such as fiber pull-out, delamination, poor dimensional accuracy, and inconsistent surface finish when processed by conventional cutting or grinding techniques. These limitations emphasize the necessity of non-contact, non-thermal machining approaches like EMM.

Although several studies have reported the successful application of EMM on either metallic or composite materials individually, a comprehensive comparative analysis of the machining performance across both types of materials under similar input parameter conditions is lacking. Most research has focused on optimizing parameters for a single material system without addressing how different materials respond to variations in voltage, electrolyte concentration, inter-electrode gap, and pulse frequency. This gap in knowledge restricts the development of a generalized understanding of EMM for diverse material categories.

Therefore, the present research is motivated by the need to explore and compare the influence of critical EMM input parameters on two distinctly different material systems: Inconel 718 alloy and fiber-reinforced composites. By adopting a systematic design of experiments (DOE)-based approach, the study investigates key machining responses such as material removal rate (MRR), surface

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roughness (Ra), and overcut under controlled conditions. Through comparative analysis, this work not only identifies the optimal parameters for each material but also establishes guidelines for tailoring EMM processes across heterogeneous materials.

The significance of this study lies in bridging the research gap by providing a direct comparison of machining performance, thereby contributing to the advancement of precision micromachining technologies. The insights gained from this work can guide industrial practitioners in selecting appropriate parameter ranges, improving process efficiency, and ensuring superior surface quality for both metallic superalloys and advanced composites.

2. Materials and Methods

2.1 Materials

The materials selected for this study represent two distinct classes of engineering materials: a nickel-based super alloy and a fiber-reinforced composite. **Inconel 718 alloy** was chosen owing to its excellent high-temperature strength, oxidation resistance, and extensive applications in aerospace and power generation industries. Cylindrical specimens of Inconel 718 were prepared with dimensions suitable for micromachining trials. For comparative analysis, **fiber-reinforced composite specimens** consisting of polymer matrix reinforced with high-strength fibers were employed. These composites were selected due to their growing usage in lightweight structural and biomedical applications, where precise micro-feature generation is increasingly required.

2.2 Equipment and Setup

All experiments were conducted on a **custom-designed Electrochemical Micromachining (EMM) setup**. The system was equipped with a **programmable power supply**, capable of delivering controlled voltage and pulse signals, ensuring accurate regulation of electrical input parameters. An **electrolyte circulation system** with adjustable flow rate was incorporated to maintain stable electrolyte conductivity and remove machining by-products efficiently. Workpiece holding was achieved through a **precision fixture assembly**, ensuring consistent inter-electrode alignment and minimizing vibration during trials.

2.3 Electrolyte

The electrolyte plays a vital role in determining dissolution rate, surface quality, and dimensional accuracy during EMM. In this investigation, an **aqueous sodium nitrate ($NaNO_3$) solution** was used as the electrolyte due to its stable electrochemical properties and reduced tendency to cause stray machining compared to other electrolytes. To evaluate its effect on machining performance, electrolyte concentration was varied systematically in the range of **5–25 g/L**. The solution was continuously circulated during machining to ensure uniform ion transport and avoid localized heating.

2.4 Process Parameters Studied

Four critical **input parameters** were selected based on their dominant influence on machining performance:

- **Applied Voltage (5–20 V):** Determines the rate of anodic dissolution and directly affects the material removal rate.
- **Inter-electrode Gap (10–50 µm):** Affects machining precision and overcut, with smaller gaps favoring higher current density.

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- **Electrolyte Concentration (5–25 g/L):** Governs conductivity of the electrolyte, influencing surface finish and stability of machining.
- **Pulse Frequency (10–50 Hz):** Regulates spark duration and electrolyte refresh time, impacting uniformity of material removal.

These parameters were varied in a controlled manner according to a **Design of Experiments (DOE)** approach, enabling systematic investigation of individual and interactive effects on machining performance.

3. Methodology

To ensure a systematic and reliable investigation of the Electrochemical Micromachining (EMM) process, a **Design of Experiments (DOE)** approach was employed. DOE was chosen because it enables the identification of critical input parameters, their individual effects, and interactive influences on machining performance while minimizing the number of experimental trials.

3.1 Experimental Design

Four key input parameters—applied voltage, inter-electrode gap, electrolyte concentration, and pulse frequency—were selected based on prior literature and their expected influence on machining outcomes. The levels for each parameter were chosen within practical ranges (voltage: 5–20 V, inter-electrode gap: 10–50 µm, electrolyte concentration: 5–25 g/L, pulse frequency: 10–50 Hz). A factorial experimental design was constructed to study both main effects and interactions among parameters.

3.2 Output Responses

Three machining performance indicators were selected as **output responses**:

1. **Material Removal Rate (MRR):** Calculated based on the weight loss of the specimen before and after machining, providing a measure of machining efficiency.
2. **Surface Roughness (Ra):** Evaluated using a profilometer to assess the quality of machined surfaces.
3. **Overcut:** Determined through microscopic measurements of machined features to quantify dimensional accuracy.

3.3 Statistical Analysis

The collected experimental data were subjected to **Analysis of Variance (ANOVA)** to identify statistically significant parameters and their contribution ratios. ANOVA helped determine whether the observed variations in machining responses were due to specific process parameters or random experimental error. Regression models were also developed to establish predictive relationships between input parameters and output responses.

3.4 Comparative Evaluation

To highlight the differences in machining behavior, a **comparative analysis** was performed between Inconel 718 alloy and fiber-reinforced composite specimens under identical machining conditions. This enabled the identification of material-dependent parameter sensitivity, illustrating how metallic and composite substrates respond differently to changes in EMM parameters.

The research methodology thus followed a sequential plan:

1. Selection of materials and parameters.

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2. DOE-based execution of machining trials.
3. Measurement of responses (MRR, Ra, Overcut).
4. Statistical and comparative analysis of results.
5. Identification of optimal conditions for each material system.

This structured methodology ensured both **scientific rigor** and **practical relevance**, allowing the results to serve as a reference for tailoring EMM processes to different engineering materials.

4. Experimental

The experimental trials were conducted on a specially designed Electrochemical Micromachining (EMM) setup. A cylindrical copper tool electrode was employed as the cathode due to its high conductivity and ease of fabrication. The workpiece specimens—Inconel 718 alloy and fiber-reinforced composites—were mounted on a precision fixture to maintain alignment and ensure stable inter-electrode gaps during machining.

Prior to machining, the specimens were cleaned using acetone and distilled water to remove contaminants that could affect electrochemical reactions. The electrolyte, an aqueous sodium nitrate ($NaNO_3$) solution, was continuously circulated across the machining zone at a controlled flow rate to ensure uniform ion transport and removal of machining by-products.

During each trial, applied voltage, inter-electrode gap, electrolyte concentration, and pulse frequency were varied according to the DOE plan. Machining was performed for a fixed duration to enable comparative evaluation across all experiments.

Post-machining, the specimens were thoroughly rinsed and dried before measurements. The Material Removal Rate (MRR) was calculated using the weight-loss method, where pre- and post-machining weights were recorded using a high-precision digital balance. The surface roughness (Ra) of the machined area was analyzed with a profilometer to assess surface integrity. To evaluate dimensional accuracy and overcut, machined features were examined using an optical microscope, and measurements were compared with intended feature dimensions.

This systematic approach ensured reliable data collection and repeatability of results across different parameter combinations.

4.1 Results

The analysis of experimental data revealed the following key trends:

1. Effect of Voltage and Inter-Electrode Gap
    - Higher applied voltages increased the anodic dissolution rate, thereby improving the Material Removal Rate (MRR).
    - However, excessive voltage and reduced inter-electrode gap led to uncontrolled dissolution, resulting in larger overcut and reduced dimensional accuracy.
2. Machining Behavior of Composites vs. Inconel
    - Composites generally exhibited lower MRR compared to Inconel due to their heterogeneous microstructure and lower conductivity.
    - Despite lower removal rates, composites produced smoother surface finishes under optimized conditions compared to Inconel.

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3. Effect of Electrolyte Concentration
    - Electrolyte concentration was observed to play a dominant role in surface roughness.
    - Higher concentrations improved conductivity and material dissolution but occasionally caused localized pitting, particularly in Inconel.
4. Effect of Pulse Frequency
    - Pulse frequency was critical in maintaining MRR stability.
    - Lower frequencies allowed sufficient electrolyte refresh but reduced machining speed, whereas higher frequencies improved speed but risked uneven dissolution.
5. Comparative Sensitivity
    - Inconel required tighter parameter control to maintain dimensional accuracy due to passive oxide film formation and high conductivity.
    - Composites were comparatively more tolerant to parameter variations but required careful control of electrolyte concentration to avoid fiber–matrix interface degradation.

4.2 Discussion

The findings indicate that electrochemical micromachining behaves differently for metallic alloys and composite materials, underscoring the need for tailored optimization. For Inconel 718, the main challenge lies in controlling dimensional accuracy. The alloy's high electrical conductivity accelerates dissolution under higher voltages, leading to overcut. Additionally, the presence of a passive oxide film tends to disrupt uniform machining, necessitating fine-tuning of voltage and electrolyte concentration.

For composite materials, the challenge is primarily in achieving uniform surface quality. Their heterogeneous structure, comprising conductive fibers and insulating matrices, leads to uneven dissolution when parameters are not optimized. Lower voltages and moderate electrolyte concentrations were found to produce more uniform surfaces with reduced risk of fiber pull-out or delamination.

The comparative analysis highlights that while Inconel benefits from aggressive parameter settings for higher productivity, composites demand moderate and balanced settings for surface integrity. These observations confirm that a universal parameter set cannot be applied across materials, and process optimization must consider material-specific characteristics.

5. Conclusion

This experimental and comparative study validates the effectiveness of Electrochemical Micromachining (EMM) for both Inconel alloys and fiber-reinforced composites. The research demonstrated that input parameters such as voltage, inter-electrode gap, electrolyte concentration, and pulse frequency exert significant influence on machining outcomes, but their impact varies with material type. Optimized parameter combinations enabled enhanced material removal rates while maintaining surface integrity and dimensional accuracy. For Inconel, strict control of voltage and gap size is necessary, while for composites, electrolyte concentration and pulse frequency play a more decisive role in achieving stable machining.

The results establish EMM as a viable and versatile machining method for advanced engineering materials, with potential for high-precision, damage-free micro-feature fabrication in aerospace,

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biomedical, and energy applications.

6. Future Scope

- Investigation of hybrid electrolyte compositions for enhanced machining stability.
- Integration of advanced pulse modulation techniques to further improve precision.
- Exploration of nano-composites and functionally graded materials under EMM.
- Application of machine learning-based optimization models for real-time parameter control.

Nomenclature

- EMM – Electrochemical Micromachining
- MRR – Material Removal Rate
- Ra – Surface Roughness
- DOE – Design of Experiments
- ANOVA – Analysis of Variance

Abbreviations

- µm – Micrometer
- Hz – Hertz
- g/L – Grams per liter
- V – Voltage

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Chapter 2

Effect of Tougher on Moisture Absorption and Glass Transition Temperature of Glass / Phenoliclaminates

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Abstract:

Composite materials are a blend of two or more components, one of which is made of stiff, long fibers and the other is matrix, which holds the fibers in place. Such combinations exhibit the best properties of the individual material possess. Composites like laminated plywood, reinforced concrete etc., has been in use for a number of years but the advancement in recent years has been in fiber/ reinforced plastic. The use of light building materials for various applications such as airplanes, automobiles etc., has given rise to synthetic polymeric materials. Fiber Reinforced Plastic (FRP) is one such material, which is a combination of a resin system, reinforced with a glass fabric. It has a tendency to undergo deterioration in strength due to moisture absorption. Moisture diffusion study is very important for the successful design of FRP material. As a part of project study, a phenol- formaldehyde resin system and glass fiber were selected. A laminate of the two materials was prepared and the effect of a hydrothermal environment on moisture absorption and its effect on glass transition temperature (Tg) were studied.

Key words: Fiber reinforced plastic, phenol formaldehyde resin, glass transition temperature, thermoplastics

1. INTRODUCTION

In the continuing quest for improved performance, which may be specified by various criteria including less weight, more strengths and lower cost currently used materials frequently reach the limit of the usefulness. The material scientist, Engineers & Scientist are always striving to produce either improved traditional materials / completely new materials. Composites are an example of the later category. Composite materials are macroscopic combination of two or more distinct materials having discreet and recognizable interface separating them. The composites of interest, however, are the synthetic, manmade materials, processing high strength and / or stiffness relative to weight, which is used in high performance structural applications because of these properties. The narrower definition of composites therefore becomes more specific and can be restricted to those combinations of materials that contain high strength/stiffness fiber reinforcement supported by high performance matrix material.

1.1 Application of Composites

Polymer matrix Composites are currently being used in a wide range of products to suit various industrial requirements because of their design flexibility, high performance characteristics, low potential cost and energy saving advantages. These materials are thus used in various fields like aerospace application, defense, chemical, electrical, electronics, medical, agriculture, and in energy sector. Thus, Composites find applications in needs common man to high technology application. Some of the important application is

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summarized in the table 1.

Table 1. Application of Composites

S.No	CATEGORY	APPLICATION
1	Aerospace	Aircraft wings and rudders, fuselage of Small planes and gliders, rocket motor casing etc.
2	Agriculture	Irrigation pipes, green house covers, Channel linings etc
3	Automobile	Vehicle bodies, Dash boards, helmet, fan belts etc.
4	Medical /Biomedical	Artificial human implants and limbs
5	Construction	Partition panels, doors, furniture, and water tanks
6	Chemical industry	Piping, Ducting, plating baths, pressure / storage Vessels.
7	Defense	Bulletproof vests, gun cases, temporary shelters, Portable bridges, containers etc.
8	Electrical/ Electronics	Insulators, PCB and antenna reflectors.
9	Marine	Ship borne equipment, light boats etc
10	Pollution control	Fan blades for windmills and exhaust systems, Chlorinating and water treatment equipment etc

In aerospace application, the term composite Structure refers to fiber /resin combination where in the fiber is embedded in the resin called matrix but retains its identity. The fibers are strong and stiff relative to the matrix and are generally orthotropic (having different properties in two different directions). Fiber Reinforced Plastic (FRP) is one such material, which is a combination of a resin system, reinforced with a glass fabric. It has a tendency to undergo deterioration in strength due to moisture absorption. Moisture diffusion study is very important for the successful design of FRP material. As a part of project study, a phenol- formaldehyde resin system and glass fiber were selected.

Novalacs are the acid catalyzed phenolic resins. Usual phenol to formaldehyde ratio is 1: 0.8. Novalacs are thermoplastic in nature. General acid catalysts employed are sulphuric acid and oxalic acid. Novalacs are fusible and soluble. They undergo cross-linking only on heating with a cross linking agent because of low methylene group density. The aim of the project was to study the effect of toughner of Novalac resin on thermal properties. Thermal properties Tg determination and moisture absorption studies were conducted and compared.

2. EXPERIMENTAL PROCEDURE

2.1 Preparations of the blends of resins with polycarbonate

The material selected for the preparation of blends was polycarbonate. He blends were prepared by the solution blending method. For this, two solutions were prepared a solution of Novalac resin in methanol and a solution of polycarbonate in chloroform. The solutions were mixed and stirred for through blending. More chloroform is added if any lumps formed. The quantity of polycarbonate to be added found by calculation compositions of polycarbonate in blends prepared were 6%, 8% and 10%.

2.2 Preparation of prepregs

13 layers of 300 x 300 mm E- glass fiber cloth has cut and weighed. The weight of the resin to be added to prepare the laminate is found. The resin to fiber ratio is arbitrarily fixed as 60:40. The required amount of resin to prepare the laminate is calculated. The curing agent (HMTA) containing resin is then in minimum quantity of methanol solvent to get the required viscosity for impregnation the glass clothe. The solution obtained thus is impregnated very well on the glass cloth by hand layup method using a brush. The resin-impregnated cloths are then dried in the air. The dried prepregs were weighed and stacked. The blend of the Novalac resin and polycarbonate is prepared according to the procedure.

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2.3 Processing procedure

The stacked prepregs were pre heated at 80 ^{0}C in a Therelak heating woven for half an hour. After pre heating, the prepregs were kept in between two plain aluminum plates and inserted in between two heating plates of the hot press instrument. The plates are closed and the required heating is started. The Cure temperature and the time duration are as fallows. Firstly 100 ^{0}C and 130 ^{0}C are applied for 10 minutes each. The prepregs were heated at 150 ^{0}C for 15 minutes and a pressure of 50 psi is applied. Finally, a temperature of 180^{0}C is applied for one hour. After the complete cycle of pressure and temperature the system is allowed to cool to room temperature. Then the laminate is removed. The sides without proper impregnation were removed. The weight of the laminate is noted.

2.4 Preliminary Studies of the laminate

The laminates prepared were subjected to the following tests. Different codes were given to each laminate for identification. Codes and their description are given in the table 2.

Table 2: Codes of the laminates and their description

Sl. No	CODE	DESCRIPTION
1	CPF	Commercial Novalac resin/Glass fiber laminate
2	C6	Commercial Novalac resin + 6% polycarbonate / Glass fiber laminate
3	C8	Commercial Novalac resin + 8% polycarbonate / Glass fiber laminate
4	C10	Commercial Novalac resin + 10% polycarbonate / Glass fiber laminate

2.4.1 Global weight fraction (GWF)

The weight and area of the laminate were observed. The aerial density of the glass cloth used in laminate is calculated by knowing the area and weight of the cloth. And by knowing the number of the number of layers of cloths used in the laminate we can calculate the GWF.

2.4.2 Fiber weight fraction (FWF)

Small pieces of a laminate from different portion were cut. These pieces were taken in the ceramic boat and weighed. These boats were kept inside a Muffle Furnace kept at 600^0C for 30 minutes. After getting the boats cooled again weight is noted and the corresponding fiber weight fraction is calculated. The average value vale is taken.

2.5 Thermal Properties

Since phenolic resins are thermally very stable, their thermal properties are very important. Important thermal properties are flammability, Tg determination etc.

2.5.1 Differential Scanning Calorimetry (DSC) for Tg determination

DSC is used to determine the glass transition temperature (Tg) of the laminate. For this, a small piece of the specimen is crimped and kept in sample pan. The cell is then introduced into the DSC instrument and heated at a constant rate of heating. Heating rate was 10^0C/minute. As the temperature rises, the transition of the sample commences and is continuously monitored by the instrument and Tg is determined.

2.5.2 Moisture Absorption Studies

The continuous increase in demand of lighter materials of construction has caused the development of the technology of reinforced plastics even more rapidly. This increase in technological standards is mainly concentrated to tailor the required properties.With this increase in interest of variety of composite degradation in thermal and other properties on exposure to different environmental condition has also increased.

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The final effect of on the component is to degrade the material of composite t various levels, depending on degradation mechanism and duration of exposure. Course of degradation involves visual surface damage, resin degradation, resin fiber debonding and finally leading to complete failure of the composite.

Main degradation mechanism involved is

- Thermoxidative degradation
- Radiation degradation
- Hydrolytic degradation

It has been established that moisture in atmosphere causes the most devasting effects on the service of life of reinforced plastics the moisture penetrating the reinforced plastics through a diffusion mechanism. These degradations are most pronounced in polyester resins due to the presence of the hydroxyl group (OH) in their structure. Weights of samples at different time interval were noted and moisture absorption were calculated using Fickian Diffusion Model.

Table 3: Moisture absorption values and time intervals (Sample C6)

Square root time	% Moisture gain
4.55	0.772
12.87	1.906
13.77	1.9809
15.419	1.991
20.188	2.034
27.235	2.012
30.12	2.020

Table 4: Moisture absorption values and time intervals (Sample C8)

Square root time	% Moisture gain
4.55	0.317
13.77	1.664
16.958	1.8198
20.188	1.895
21.86	1.876
25.416	1.91
27.235	1.903

Table 5: Moisture absorption values and time intervals (Sample CPF)

Square root time	% Moisture gain
4.55	0.342
11.88	0.884
12.87	1.025
13.77	1.216
15.419	1.305
16.958	1.426
20.188	1.625
21.863	1.729
24.1609	1.853
25.416	2.034
27.235	2.117
28.44	2.198
30.120	2.23

Table 6: Moisture absorption values and time intervals (Sample C10)

Square root time	% Moisture gain
4.55	0.378
11.88	1.311
24.16	1.888
25.416	1.906
30.12	1.909

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Table 7: Values of diffusion co- efficient (Dc) and maximum % moisture gain (%m_m)

Laminate Code	Maximum% Moisture gain	Time (hrs)	Diffusion co-Efficient (mm^2/sec)
CPF	2.2	907.25	$4.768 X 10^{-7}$
C6	2.0	907.25	$8.547 X 10^{-7}$
C8	1.93	741.75	$11.936 X 10^{-7}$
C10	1.9	907.75	$15.73 X 10^{-7}$

3. Results and Conclusions

The results obtained clearly indicate that % moisture absorption and Tg decreases to the optimum level with the increase toughner content.

3.1 Tg determination by DSC

Tg values of different laminates were determined with the help of DSC. The values are tabulated in the table 8.

Table 8. Tg values of laminates

Sl. No	Specimen Code	Tg (^{0}c) (Before Saturation)	Tg (^{0}c) (After Saturation)	ΔTg
1	CPF	199	170	29
2	C6	195	134	51
3	C8	192	129.4	62.6
4	C10	178	126	52

Tg values are showing a decreasing trend as the percentage of polycarbonate increases in the blend. This is because of the plasticizing action of polycarbonate action, which toughens the brittle Novalac matrix. This is the normal trend observed in all other blend also. Tg of unmodified Novalac resin laminate is 199^{0}c and that of polycarbonate are 148^{0}c. As the percentage of polycarbonate increases in the blend, Tg values are coming towards the value of polycarbonate.

3.2 Fiber Fraction of the laminates

Fiber Fraction of the laminates was determined by Global weight fraction (GWF) and with the help of Muffle furnace. The values were found to be comparable. The values are listed in the table 9.

3.2.1 Confirmation of Fiber fraction by burn off test (by Muffle furnace method)

Weight factions estimated theoretically were checked by experimental procedure for precision by employing the methods of gravimetric analysis and weight fraction were found to be correct. Experiment was conducted by burning off previously weighed cut samples of laminate at 600^0c, which is weighed to get accurate fiber weight fraction of laminate.

3.2.2 Confirmation of Fiber fraction by GWF (Theoretical method)

GWF gives the fiber fraction of the laminates. GWF is a confirmation method for the fiber fraction. Arial density, D of the fiber used in the laminate = weight of the fiber/Area of the fiber.

$$GWF = \frac{[D \times \text{No of layers} \times \text{Area of laminates}] \times 100}{\text{Weight of laminate}}$$

Table 9: Fiber fraction of the laminates

Specimen Code	Fiber fraction (%)	
	GWF	**Muffle furnace**
CPF	62.33	60.67
C6	61.83	61.40
C8	60.55	60.21
C10	59.90	60.13

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4. CONCLUSION

- Tg is a function of moisture absorption.
- In thermoplastic composites, as the percentage of toughner increases, percentage moisture absorption decreases and hence Tg decrease.
- It has been noticed that as the toughner content increase, though the brittleness reduces the Tg also correspondingly decreases. Hence, to optimize both the properties it has been concluded that C10 gives the best results among all the samples used. Percentage moisture gain of C10 sample is also the least.

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Chapter 3

The Digital Revolution in Education: From Traditional Classrooms to E-Learning

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Abstract

This paper explores the digital revolution in education, analyzing its profound impact on learning methodologies and accessibility. It employs a descriptive research approach, integrating insights from sociology, pedagogy, and technology to present a holistic perspective. The study compares the benefits and challenges of e-learning with traditional classroom models, highlighting trends like online education and the role of educational technology in fostering a more personalized and interactive learning environment for a new generation of students.

Keywords: Digital Revolution; E-learning; Educational Technology; Online Education; New Generation;

1. Introduction

Education is undergoing a profound transformation. The long-standing tradition of in-person classroom instruction is no longer the singular or even primary mode of learning for many. Driven by rapid advancements in technology and the internet, the landscape of education is evolving to be more flexible, accessible, and personalized.

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Data from the Babson Survey Research Group shows that as early as 2022, over 30% of higher education students in the United States were taking at least one distance learning course, highlighting a widespread embrace of this new model. This shift has not only made education more practical for a diverse audience of learners but has also been accelerated by global events. The onset of the COVID-19 pandemic, for example, forced the closure of schools and universities worldwide, impacting 1.37 billion students and their educators. This event underscored the critical need for a resilient, user-friendly, and adaptable educational format like e-learning.

2. Materials and Method

This paper adopts a descriptive research design, drawing on a comprehensive analysis of secondary sources including academic journals, books, government reports, and reputable news publications. The content analysis method was employed to systematically examine and synthesize the secondary data to provide a detailed overview of the e-learning phenomenon.

2.1 A Multidisciplinary Research Approach

Understanding the complexities of e-learning necessitates a multidisciplinary research approach. This method involves drawing on knowledge, theories, and methodologies from multiple academic disciplines to gain a more complete and nuanced understanding of a complex issue. For a topic like e-learning, which intersects with technology, human behavior, and societal structures, a single-discipline approach would be insufficient.

This paper integrates insights from various fields to build a comprehensive picture:

- Computer science and engineering provide the foundation for understanding the technical infrastructure, software design, and usability of e-learning platforms.
- Educational pedagogy informs the study of effective teaching methods, curriculum design, and instructional strategies in a digital environment.
- Psychology offers a lens for examining learner motivation, cognitive processes, and the psychological impacts of online education.
- Sociology and economics are crucial for analyzing the social and economic implications of e-learning, including issues of equity, access, and global market trends.

By combining these diverse perspectives, this research aims to provide a holistic and robust analysis of the shift from traditional to electronic learning, revealing its multifaceted nature and its wide-ranging impact.

2.2 Traditional vs. E-Learning: A Comparative Analysis

The fundamental differences between traditional learning and e-learning extend beyond the physical classroom. While traditional education is built on an instructor-centric model with knowledge transmitted primarily through lectures, e-learning fosters a learner-centric approach that emphasizes self-paced, abstract, and collaborative learning. The following table provides a clear comparison of the two models across various dimensions.

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Table 1

Feature	Traditional Learning	E-Learning
Learning Paradigm	Instructor-centric, emphasizes knowledge production and passive reception.	Student-centric, prioritizes knowledge processing and active participation.
Cost	Lower initial investment in infrastructure and technology.	Higher initial costs for infrastructure, software, and training.
Location & Time	Fixed location and scheduled class times.	Flexible, allows learning from any location at any time.
Engagement	Passive, lecture-centric approach; student relies on the teacher.	Fosters self-learning, autonomy, and efficacy through interactive content.
Audience	Primarily for students of a specific age group; work and study are separate.	Caters to diverse groups (e.g., housewives, factory workers); can be integrated with employment.
Content Format	Primarily text-based in books; images and technical accuracy may be limited.	Multi-modal, including text, static and animated images, videos, and simulations.
Communication	Limited to scheduled class time; questions may be constrained.	Flexible communication via email, chat rooms, and other channels.
Teacher Role	Primary source and conduit of information.	A guide, advisor, and facilitator of information.
Peers	Confined to local classmates and schoolmates.	Diverse, global peers; geographical barriers are eliminated.
Language	Aligned with the student's country of residence.	Encourages learning foreign languages for access to global content.
Enrollment	Restricted capacity based on physical	No limit; accessible to students from around the

Feature	Traditional Learning	E-Learning
	availability.	world.
Personalization	Fails to consider individual learning differences; uniform content delivery.	Tailored to meet individual needs and preferences.
Feedback	Feedback is often delayed and lacks a distinct, fulfilling role.	Emphasis on prompt and immediate feedback.
Material Updates	Educational materials are static and updated infrequently.	Easy electronic updates with the latest content.
Main Source	The teacher is the main source of information.	The teacher is an advisor and facilitator of resources.

3. The Rise of E-Learning and its Future

The emergence of e-learning is not merely a passing trend but a fundamental shift in how we learn. In the business sector, 57% of Learning and Development professionals are increasing their investment in online learning, while 37% are reducing their reliance on instructor-led training. The COVID-19 pandemic accelerated this shift, with 98% of organizations adopting virtual learning and 59% of talent developers increasing their budget for online training.

This growing popularity is driven by the accessibility and flexibility e-learning provides. Learners can pursue academic and professional goals without being confined by time or location. The cost-effectiveness is also a major factor, with online courses often being more affordable and offering flexible payment options.

The global e-learning market is projected to grow significantly. As of 2022, it was valued at $399.3 billion and is expected to reach an impressive one trillion USD by 2032. This growth is fueled by several

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factors, including the globalization of workforces, the need for continuous skill development, and the proven resilience of online platforms during crises.

4. The Future is Now: Key Trends in E-Learning

The future of education will be shaped by several key trends that are already taking hold.

- Virtual and Mobile Learning: The flexibility of e-learning is highlighted by the growing trend of mobile learning, with 57% of employees preferring to access learning modules on the go. During the pandemic, 23% of students attended live-stream classes, and 67% of parents were satisfied with this format. Looking ahead, a significant majority of parents anticipate a future where virtual attendance is the norm for both college and K-12 students.
- Independent Learning: With over 35% of employees seeking self-directed learning opportunities, and 83% of U.S. citizens anticipating a shift toward a self-service model in education, platforms are adapting to meet this demand. Learning Management Systems (LMS) are empowering students to learn at their own pace, focusing on subjects of particular interest.
- Individualized Tutoring: Personalized one-to-one tutoring is highly effective and increasingly popular online. This method allows students to receive 100% of the teacher's attention, and its success during the pandemic has led to 14% of parents planning to invest in online tutoring for their children's future education.

- Immersive Technologies: A substantial 39% of Learning and Development professionals believe that Virtual Reality (VR) and Augmented Reality (AR) will have a significant impact on online learning. These technologies can simulate real-world situations, providing hands-on, experiential learning that goes beyond traditional lectures.
- Artificial Intelligence (AI): AI and machine learning are making personalized learning experiences more attainable. By analyzing user data, these systems can provide tailored course recommendations, helping learners and businesses address skills gaps efficiently. A notable 79% of learners are interested in using personalized course recommendations aligned with their career goals.

5. Conclusion

The ascendancy of online education has fundamentally reshaped the educational landscape, presenting both new opportunities and challenges for traditional institutions. Post-pandemic, e-learning is evolving to be more inclusive and collaborative, offering a flexible and cost-effective alternative to traditional learning. It provides a global platform for diverse learning preferences, enabling individuals to pursue their academic and professional goals without geographic or temporal constraints. For this digital revolution to be truly equitable, governments and educational institutions must develop inclusive online education policies that ensure access for all, from the socially and economically privileged to those from poor and rural backgrounds. Failure to do so risks exacerbating existing societal disparities and creating a new form of educational inequality. The link between school education and the internet is now unavoidable,

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making strategic policy and resource allocation a critical priority for the future.

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Chapter 4

Redefining Human Capital Management with HRIS: Pathways to HR 4.0

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Abstract

Industry 4.0, which originated in Germany, highlights the combination of digital technologies in processes and data exchange to increase efficiency in operations. Following this, HR 4.0 is a logical follow-up, with the focus being placed on the digitalization of human resource management activities. This development includes electronic Human Resource Management (e-HRM), Human Resource Information Systems (HRIS), and complete digitization of HR processes. By automating HR procedures and enabling data-driven decision-making, HRIS is a key enabler that enables businesses to smoothly implement HR 4.0. Adoption of HR 4.0 not only transforms HR procedures but also aligns them with the Industry 4.0 initiative, promoting innovation, agility, and sophisticated decision-making across the entire company. This modification highlights how crucial HRIS is to the HR 4.0 model and how it is changing traditional HRM into a more dynamic, tech-driven industry. The use of digital tools in HR operations provides instant access to data, increases employee participation, and enables strategic workforce planning. Furthermore, HR 4.0 promotes differentiated employee experiences

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through automation and analytics, leading to increased productivity and job satisfaction. While organizations face mounting complexity and competition, HR 4.0 provides a compass for agile adaptation and long-term competitiveness in talent management. In addition, improvements in machine learning and artificial intelligence in HRIS enable companies to forecast workforce trends, optimize hiring, and improve retention.

Keywords: HRIS; HR 4.0; digitization; efficiency; digitization.

1. Introduction

The term "industry 4.0" was coined in Germany and highlights the use of technology in processes and data interchange. HR 4.0 would ultimately follow directly from Industry 4.0 activities. It would entail the digitization of HRIS, e-HRM, and HRM processes. The main HRM tasks in an organization include hiring and selection, pay, general administration, employee welfare, communication, organizational development, performance management, employee motivation, rewards and recognition, and training and development. The HR department's regular administrative and general tasks are made somewhat easier by the HR software, which automates them. These HRIS tools, which can be used to update and record personnel data, improve the efficacy and efficiency of the recruiting and selection process. An HRIS is used to collect and store employee data. HRIS facilitates the interview, confirmation, and candidate tracking processes. It can also offer businesses several cost-related advantages by streamlining the functional activities. These systems also help with accounting, payroll, managing employee benefits and leaves, and keeping an eye on employee engagement, performance, and training. The HRIS is one of the primary instruments for steering the business toward HR4.0.

1.1 PRIMARY OBJECTIVE

- To evaluate how HRIS affects HR 4.0's mediating variables

1.2 SECONDARY OBJECTIVE

- To evaluate the extent to which HRIS improves overall organizational effectiveness.
- To determine the significant impact that HRIS plays in the hiring process. To make it easier for people to use HRIS when making decisions.
- To examine how HRIS might enhance worker performance.

2. Literature Review & Methodology

2.1 Research Methodology

For this study, primary and secondary sources of data were gathered. Data was gathered via Google Forms and questionnaires sent as links via mail. A standardized questionnaire for this study was created and given to the participants. The researcher created a structured questionnaire with both closed-ended and open-ended questions. Convenience sampling that is not based on probability is utilized. 155 was chosen as the sample size. Only 111 samples out of 155 responded. SPSS was used to analyze the data.

2.2Review Of Literature

Menant, Gilibert, and Sauvezon (2021) define HRIS as a system that includes procedures, methods, people, and functions for collecting, storing, rehabilitating, analyzing, comprehending, and sharing data related to an organization's human resources. The idea of buying

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hardware and software applications facilitates HRM practices, policies, and strategies. Payroll, induction, training, incentives, career management, skills and talent management, succession planning, employee assessments, and recruitment management are just a few of the numerous applications that HRIS offers. All things considered, HRIS can also be defined as an enabling computerized system that makes it easier to manage workforce information through the managerial and strategic decision-making processes of an organization.

Gupalasetty, Sandeep (2016), Software with a database that allows for the entry, saving, and modification of employee data is known as HRIS. It makes it possible for everyone to view and access important personnel data in detail. HRM usually uses IT as HRIS. It is a comprehensive system that collects and saves data for use in human resources analysis and decision-making. HRIS is a sophisticated system that primarily relies on employee accountability to manage complex organizational issues. A human resources information system, which is part of an organization's structure, has developed into a dynamic tool for encouraging teamwork, information sharing, and better work performance and productivity both within the organization and between employees. In order to handle issues like increasing organizational demands, more thorough information use, and increased information needs, as well as continuous pressure to reduce costs and turn HR into a strategic business partner, today's organizations require an effective HRIS. HRIS has become a vital instrument for enhancing the efficacy and performance of organizations. Sergio (2010). In order to reduce expenses, reduce the number of managers, standardize HR practices, or simply add strategic value to the organization's decision-making process, HRIS is integrated into the problems that businesses face. Everyone acknowledges that HRIS is a very effective tool for enhancing an organization's effectiveness across various organizational practices, including HR performance. Parumasur and Kumar (2013).

Although HRIS may be viewed as an essential business step, Brown (2008) warned that if it is not a helpful tool for HR tasks, it may actually hinder efficiency rather than improve it. An efficient HRIS supports the fundamental administrative processes of an organization, such as management decision-making, technology selection, and organizational reporting structures. HRIS has developed into a proactive tool that enhances job performance and efficiency by facilitating the development of relationships between employees and their organization. Moritz, Lengnick, and Hall (2017).

According to Bach (2019), organizational performance is significantly impacted by the efficacy of HRIS use, as evidenced by the range of applications for the software systems. Some companies spend a lot of money on HRIS, but they are unable to measure the benefits of the system. It will be possible to create a collaborative, self-service, real-time, information-based workplace in the coming years as technology develops.

Ankrah&Sokro (2016) found that the use of HRIS improves the effectiveness of strategic HRM after investigating the system. The use of HRIS, which could be considered strategic HR planning, improves employee performance, decision-making contributions, cost and time savings, day-to-day operational issues, the impact of high-quality information, and employee development commitment. Silva and Lima (2018) Furthermore, strategic human resources (HR) encompass not only the planning and implementation of activities but also the

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control of results, which need to be linked to the organization's strategy by means of the resources' proactive vision. To support these activities, HRIS can provide data that monitors the internal and external environment to identify threats and opportunities that impact organizational strategy. Its problem-solving skills can also support the development of human resources in a high-quality and productive manner.

Establishing HR 4.0 requires decentralized decision-making, technology assistance, high-quality information, and connectivity.

- HI: HRIS facilitates the development of connections inside and between HR procedures.
- H2: HRIS facilitates decentralized decision-making.
- H3: HRIS facilitates the development of organizational efficiency. H4: HRIS ensures data management

3. Findings And Interpretation

Table 1: level of HRIS used in organization

OPTIONS	FREQUENCY	PERCENTAGE (%)
Operational level	7	6
Recruitment, compensation and benefits level	11	10
Supporting workforce planning	21	19
Integration of data	48	43
All the above	24	22
Total	111	100

From the above table, it is inferred that 6% of the employees use HRIS for operational level, 10% of the employees use HRIS for recruitment, compensation and benefits level, 19% of the employees use HRIS for Supporting workforce planning, 43% of the employees use HRIS for integration of data and 22% of the employees use HRIS for all the above options.

HI: HRIS helps build interconnection between and within the HR processes

The hypothesis is checked by analyzing the impact of HRIS on recruitment and appraisal process

CHART 1

HRIS HELPS BUILD INTERCONNECTEDNESS WITHIN RECRUITMENT PROCESS

From the data, it is inferred that 5% of the employees Strongly Disagree that HRIS does not help with the recruitment process, 24% of the employees Disagree that HRIS does not help with the recruitment process, 20% of the employees are neutral that HRIS help with the recruitment process, 39% of the employees agree that HRIS help with the recruitment process and 12% of the employees Strongly agree that HRIS help with the recruitment process.

CHART 2

WAYS IN WHICH HRIS HELPS WITH RECRUITMENT PROCESS

Table 2: WAYS IN WHICH HRIS HELPS WITH RECRUITMENT PROCESS

OPTIONS	FREQUENCY	PERCENTAGE (%)
Tracking candidate information	43	39
Enables recruiters tomatchjob openings	20	18
Helps in guiding the hiring process	23	21
Availability of resumes	11	10
None of the above	14	12
Total	111	100

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From the above, it is inferred that 39% of tracking candidates information helps HRIS with the recruitment process, 18% HRIS enables recruiters to match job in the recruitment process, 21% HRIS helps in guiding the hiring process in the recruitment process, 10% of availability of resumes helps HRIS with the recruitment process and 12% of goes with none of the above mentioned.

CHART 3

HRIS HELPS TO IMPROVE PERFORMANCEAPPRAISAL PROCESS

From the above, it is inferred that 41% of faster production of reports from HRIS help to improve employee performance, 11% of enabling development training helps to improve employee performance, 15% of encouraging open communication helps to improve employee performance, 22% of accurate performance tracking helps to improve employee performance and 11% of easier goal setting helps to improve employee performance. H2: HRIS assists in decentralized decision making

Table 4: Existence of HRIS and effective decision making

Value		df	Asymptotic Significance (2- sided)
Pearson Chi-Square	385.877a	16	<.001
Likelihood Ratio	257.112	16	<.001
Linear-by-Linear Association	104.124	1	<.001

From the above table it is inferred that the Chi-square value is 385.877 and value of significance is .001 which is lesser than 0.05. Hence H2- "There is significant relationship between HRIS providing available data for evaluating performance and effective decision making for an employee" is accepted and H0- "There is no significant relationship between HRIS providing available data for evaluating performance and effective decision making for an employee is rejected.

H3: HRIS aids in building organization efficiency

Organizational efficiency is measured by the automation of operational work and employees being able to focus more on strategic activities.

TABLE 5 Correlation between existence of HRIS and it enabling freeing up of employees of routine work

		HRIS existence	**Freeing up of employee from routine task**
HRIS existence	**Pearson Correlation**	1	.878**
	Sig. (2-tailed)		<.001
	N	111	111

**. Correlation is significant at the 0.01 level (2-tailed).

According to the above calculated correlation coefficient there is a significant positive relationship between the two variables of existence of HRIS and it enabling employees to free up time. The significance value is 0.001 which is less than 0.05, so null hypothesis is rejected at 95% confidence level. The correlation value is 0.878 which is positive, so we can conclude that two variables have close relationship. Hence the alternative hypothesis is accepted and null hypothesis is rejected.

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TABLE 6 Correlation between the existence of HRIS and reduction of cost of office supplies

		HRIS existence	Reduced cost of office supplies
HRIS existence	**Pearson Correlation**	1	.893**
	Sig. (2-tailed)		<.001
	N	111	111

According to the above calculated correlation coefficient there is a significant positive relationship between the two variables of satisfaction with existence of HRIS and reducing the cost of office supplies. The significance value is 0.001 which is less than 0.05, so null hypothesis is rejected at 95% confidence level. The correlation value is 0.893 which is close to 1, so we can conclude that two variables have close relationship. Hence the alternative hypothesis is accepted and null hypothesis is rejected.

H4: HRIS ensures efficient data management

TABLE 7: Regression between HRIS helping recruitment process and keeping track of potential candidate

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.900a	.810	.808	.390

Coefficients

	Unstandardized Coefficients			Standardized Coefficients	t	Sig.
		B	**Std. Error**	**Beta**		
	(Constant)	1.229	.115		10.719	<.001
	HRIS help with recruitment process	.717	.033	.900	21.550	<.001

The above summary table provides the R values. The R value or correlation value is 0.900 which indicates a high degree of correlation. The coefficient table indicates the regression model predicts the dependent variable significantly well. The significant value is <0.001 which is less than 0.05. This regression is statistically significant in predicting the outcome variable. So, when HRIS is involved in the recruitment process, the tracking of potential candidates information can also be done simultaneously. Hence the alternative hypothesis is accepted and null hypothesis is rejected.

CHART 4

HRIS Provides standard quality and quantity of work produced by the employees

From the data , it is inferred that 6% of employees strongly disagree HRIS does not provide standard quality and quantity of work produced, 21% of the employees disagree HRIS does not provide standard quality and quantity of work produced, 22% of the employees are neutral that HRIS provide standard quality and quantity of work produced, 41% of the employees agree HRIS provide

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standard quality and quantity of work produced and 10% of the employees strongly agree HRIS provide standard quality and quantity of work produced.

TABLE 8 Chi-square between HRIS providing available data for evaluating effective decision making for an employee

Value		df	Asymptotic Significance (2- sided)
Pearson Chi-Square	385.877	16	<.001
Likelihood Ratio	257.112	16	<.001
Linear-by-Linear Association	104.124	1	<.001

The preceding table indicates that the chi-square value is 385.877 and the significance level is.001, which is less than 0.05.

As a result H1- "There is significant relationship between HRIS providing available data for effective decision making for an employee" is accepted and H0- "There is no significant relationship between HRIS providing available data for evaluating performance and effective decision making for an employee" has to be rejected. Hence it shows that data available for evaluating performance and effective decision making are not two different independent variables but are two variables that are dependent on each other.

APPLICATION

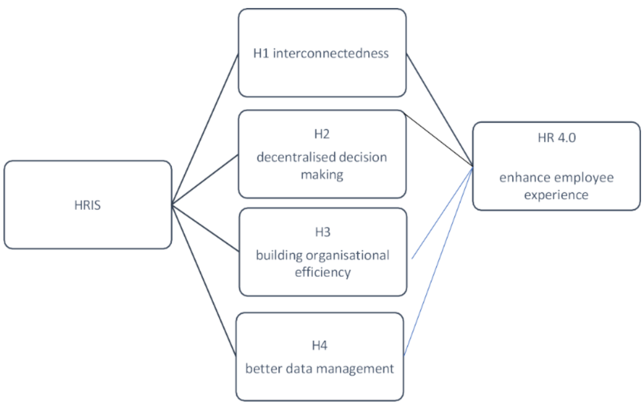

Figure. 1: HR 4.0 MODEL

The research enables the validation of the basic paradigm wherein HRIS serves as an initial step to leverage the implementation of HR 4.0

FUTURE APPLICATIONS AND CONCLUSION

A strong human resources department is always built on a foundation of certified and experienced HRIS staff members. Employees should be able to adapt to these changes and realize their full potential as companies rely more on technology to boost their financial performance. Using HRIS offers the business a number of hidden benefits. It is far more efficient to update the current managerial systems and use computerized data with all the integration of employee information stored rather than manual data because it helps maintain data with greater accuracy in less time and reduces the cost of office supplies. It is also claimed to improve HRM for administrative and analytical purposes. Consequently, HRIS holds great promise for increasing productivity and supporting HR professionals and the organization's entire workforce process.

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Chapter 5

$Wo_3/TiO_2/CeO_2$ Nanocomposites, Fabrication Approaches and their Antibacterial and Antifungal Potentials

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Abstract

$WO_3/TIO_2/CeO_2$ nanocomposites are advanced antimicrobial materials exhibiting vigorous activity under ultraviolet and visible light. The integration of WO_3, TiO_2, and CeO_2 enhances light absorption, charge separation, and reactive oxygen species (ROS) generation, enabling effective inactivation of Gram-positive, Gram-negative, and fungal pathogens. WO_3 provides visible light responsivity and electron mobility, TiO_2 ensures structural stability and antimicrobial support, and CeO_2 offers Ce_3^+/ Ce_4^+ redox cycling for sustained ROS production via oxygen vacancies. Among the various synthesis routes, solvothermal processing yields optimal morphology, crystallinity, and dispersion, resulting in superior antimicrobial performance. Antimicrobial assays reveal ROS-mediated oxidation damage to membranes, protein, and DNA, aided by strong microbial adhesion on rough, porous surfaces. The trimetallic system outperforms mono- and bimetallic oxides, offering applications in self-disinfecting surfaces, coatings, water purification, and biomedical devices.

Keywords: WO_3 / TiO_2 / CeO_2 nanocomposites; Solvothermal synthesis; Antimicrobial activity; Reactive oxygen species (ROS); Structural characterization; Environmental applications;

1. Introduction

$WO_3/TiO_2/CeO_2$ nanocomposites have emerged as a promising new class of antimicrobial materials, offering advanced capabilities to suppress, inhibit, or eliminate a broad spectrum of microbial pathogens. These multifunctional nanocomposites are particularly effective under ambient or light-assisted conditions, including exposure to ultraviolet (UV) and visible light. The unique architecture of these ternary oxide systems, composed of tungsten trioxide (WO_3), titanium dioxide (TiO_2), and cerium dioxide (CeO_2), combines the beneficial physicochemical, redox, and structural attributes of each component, resulting in a powerful synergistic effect [2,6]. This integrated approach significantly enhances their overall antimicrobial performance, far surpassing the activity of individual oxide components when used alone [4,6].

WO_3 in an n-type semiconductor with a relatively narrow band gap of approximately 2.6 to 2.8 eV, enabling strong absorption of visible light [3]. It possesses high electron mobility, allowing efficient transport of charge carriers upon irradiation. These properties make WO_3 highly suitable for incorporation into light-activated antimicrobial systems, where the generation of surface-level reactive oxygen species (ROS) plays a central role in microbial destruction [4,8]. Additionally, WO_3 is chemically stable and environmentally robust, ensuring durability and long-term activity when deployed in antimicrobial surfaces or coatings [3,6].

TiO_2, especially in its rutile phase, is one of the most widely utilized

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materials in environmental and biomedical applications due to its chemical inertness, non-toxic nature, and structural integrity [6]. Although TiO_2 exhibits a wider bandgap (3.2 eV), making it primarily responsive to UV light, it serves as an ideal supporting matrix in composite systems. Its excellent mechanical and thermal stability helps anchor the active phases. At the same time, its surface properties enhance the adsorption of microbial cells and organic contaminants, thereby facilitating closer interaction and improving ROS-mediated oxidative attack. Moreover, TiO_2 can stabilize the composite's structure and support the formation of interfacial junctions, which are essential for suppressing charge recombination [2,6].

CeO_2 plays a pivotal role in enhancing the antimicrobial activity of the $WO_3/TiO_2/CeO_2$ system due to its exceptional redox flexibility [1,5]. Its ability to reversibly transition between Ce_3^+ and Ce_4^+ oxidation states allows it to create and replenish oxygen vacancies on its surface. These vacancies are active sites for catalytic reactions and are crucial, including lipid peroxidation, protein denaturation, enzyme inhibition, and ultimately, cell death [8,9]. Furthermore, CeO_2 redox cycling enables extended antimicrobial action under visible light conditions, overcoming the UV dependency of traditional TiO_2-based systems [5,10].

As shown in Figure 1, $WO_3/TiO_2/CeO$ nanocomposites are durable, redox-active, and light-responsive materials, offering broad potential in antimicrobial technologies. Their use spans self-disinfecting surfaces, antibacterial and antifungal coatings, protective textiles, biomedical coatings, air and water purification membranes, and wound-healing dressing [2,6,9]. $WO_3/TIO_2/CeO_2$ nanocomposites exemplify a new class of advanced antimicrobial agents with the potential to revolutionize disinfection practices across medical, public health, and industrial domains. Their potent antimicrobial performance, driven by synergistic redox activity and enhanced ROS generation, ensures the effective neutralization of resistant bacterial and fungal strains, even under visible light exposure, overcoming the key limitation of conventional TiO_2-based systems [1,6,10]. However, to facilitate widespread adoption, systematic research into their biosafety, environmental compatibility, and feasibility for large-scale production is essential. These nanocomposites offer not only a robust defense against pathogen threats but also a forward-thinking strategy for designing sustainable, light-responsive antimicrobials to address future global challenges.

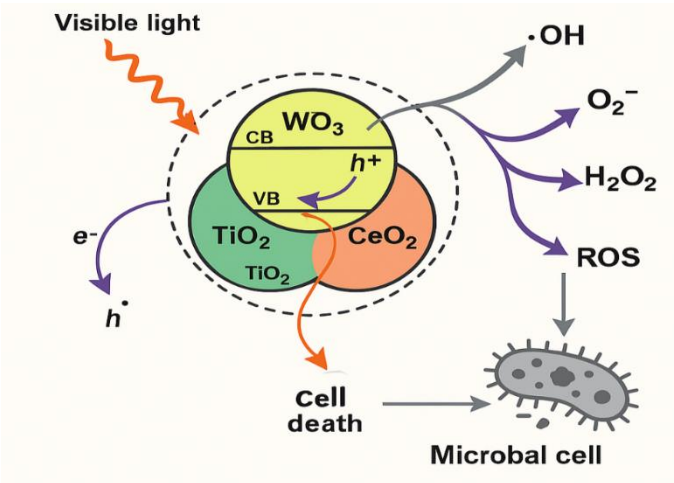

Figure 1: Antimicrobial Mechanism in WO_3 /TiO_2 /CeO_2 Nanocomposites under Visible Light.

The primary objective of this work is to identify the most efficient synthesis route for heterojunction/ternary $WO_3/TiO_2/CeO_2$ nanocomposites and to evaluate their broad-spectrum antimicrobial performance. Comparative analysis of different synthesis approaches confirms that the solvothermal methods deliver superior morphology, crystallinity, and particle dispersion, resulting in nanocomposites

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that exhibit pronounced inhibitory activity against Gram-positive bacteria (e.g, S. aureus, B.subtilis), Gram harmful bacteria (e.g, E.coli, P.aeruginosa), and selected fungal strains, emphasizing their exceptional versatility and strong potenital for real- world application [4,6,9].

2. Synthesis Methods

The synthesis of $WO_3/TiO_2/CeO_2$ nanocomposites typically employs wet-chemical routes, which enable precise control over particle morphology, stoichiometry, and surface chemistry. These methods allow for fine-tuning of active site distribution and interactions — factors crucial for optimizing antimicrobial activity.

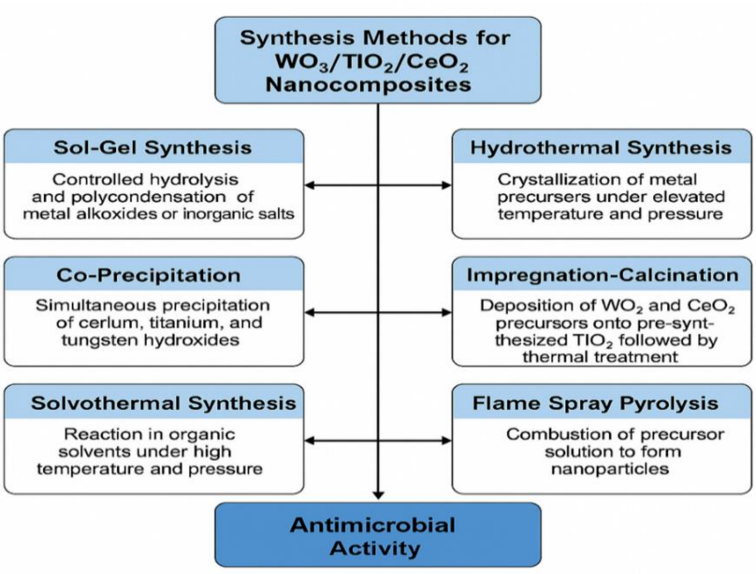

Figure 2: Synthesis methods for $WO_3/TiO_2/CeO_2$ nanocomposites and their influence on antimicrobial activity.

Figure 2 presents a schematic overview of the various synthesis methods used to fabricate $WO_3/TiO_2/CeO_2$ nanocomposites, including sol-gel synthesis, hydrothermal synthesis, co-precipitation, impregnation- calcination, solvothermal synthesis, and flame spray pyrolysis. Each method plays a critical role in influencing the morphological, structural, and antimicrobial features of the resulting nanocomposites, which are essential for antimicrobial applications.

2.1. Comparative Analysis of Fabrication Methods

A detailed comparison of these synthesis techniques is presented in Table 1, highlighting their respective advantages, limitations, and relative antimicrobial efficiencies. Among them, solvothermal synthesis emerges as the most effective, offering superior control over particle morphology, crystallinity, and component dispersion, which collectively contribute to enhance visible-light-driven antimicrobial activity. This method outperformed other approaches by facilitating uniform integration of WO_3 and CeO_3 into the TiO_2 matrix, leading to optimal redox performance and reactive oxygen species (ROS) generation under visible light [1,4,5]. While other methods, such as sol-gel and hydrothermal techniques, provide high surface area and crystallinity [2,3], they often lack the fine morphological control and dispersion efficiency achieved through the solvothermal route, making it the most suitable for developing high-performance antimicrobial nanocomposites.

Table 1: Comparative evaluation of synthesis methods for WO_3/TiO_2/CeO_2 nanocomposites

S.No	Methods	Advantages	Limitations	References
1.	Sol-Gel synthesis	High surface area, homogeneous composition, low temperature process	May require extended aging and precise control	[6]
2	Hydrothermal Synthesis	Excellent crystallinity, well-defined nanostructures	Requires high pressure, scalability issues	[7]
3	Co-Percipitation	Simple, Scalable, cost-effective	Lower crystallinity and morphology control	[8]

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4	Impregnation-calcination	Strong heterojunction formation enhances oxygen dispersion and enhances visible-light response.	Less uniform distribution of components	[9]
5	Solvothermal synthesis	Better control over morphology, high dispersion, enhanced visible-light response	Using uniform solvents may be costly.	[10,11]
6	Flame Spray Pyrolysis	Fast, scalable, suitable for industrial use	Needs precise thermal control, may have particle agglomeration	[12]

2.2. Solvothermal synthesis methods

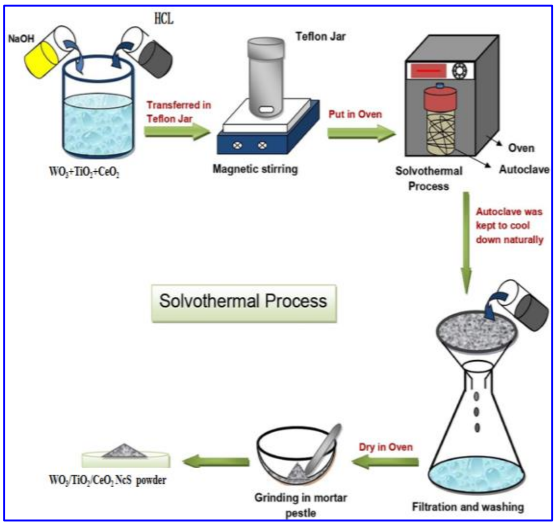

Figure 3: Solvothermal synthesis route of WO_3 /TiO_2 /CeO_2 nanocomposite powder.

Solvothermal synthesis is a highly effective method for producing $WO_3/TiO_2/CeO_2$ nanocomposites due to its precise control over morphology, dispersion, and visible-light activation. In this process, Figure WO_3, TiO_2, and CeO_2 precursors are mixed with NaOH and HCL, stirred, and sealed in a Teflon-lined autoclave. Elevated temperature and pressure promote uniform nucleation and crystal growth, yielding well-crystallized nanocomposites that are filtered, washed, dried, and ground. This method ensures homogenous integration of components, facilitating efficient charge transfers and continuous ROS generation under visible light. The resulting superoxide and hydroxyl radicals disrupt microbial membranes, proteins, and DNA, while the porous surface improves microbial cohesion, enhancing antimicrobial performance.

Furthermore, the controlled reaction environment minimizes defects and impurities, resulting in enhanced stability during repeated light cycles. The high crystallinity achieved also improves antimicrobial activity by facilitating greater reactive oxygen species production and stability. Overall, solvothermal synthesis offers a reproducible and scalable route for developing next-generation antimicrobial nanomaterials.

3.Antimicrobial Mechanism of WO_3 /TiO_2 /CeO_2 Nanocomposites

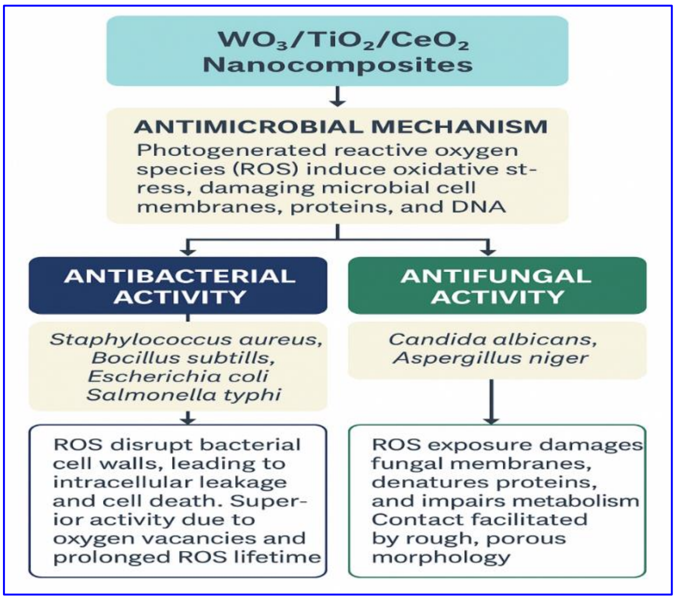

Figure 4: Flowchart Depicting the Antimicrobial Mechanism of WO_3 /TiO_2 /CeO_2 Nanocomposite.

This flowchart illustrates the stepwise antimicrobial action of $WO_3/TiO_2/CeO_2$ nanocomposites under visible light irradiation. The

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mechanism primarily involves the generation of reactive oxygen species (ROS) through efficient charge separation at the heterojunction interfaces, as illustrated in the flowchart in Figure 2.

These ROS, including hydroxyl radicals (•OH), superoxide anions (O_2^-), and hydrogen peroxide (H_2O_2), lead to oxidative damage of microbial cell membranes, proteins, and DNA, resulting in cell death

3.1. Antibacterial activity of WO_3/TiO_2/CeO_2 Nanocomposites

WO_3/TiO_2/CeO_2 nanocomposites exhibit excellent antibacterial activity against a broad spectrum of bacterial pathogens, including both Gram-positive (Staphylococcus aureus (15%), Bacillus subtilis (12%), Streptococcus mutans (14%), Enterococcus faecalis (11%), Listeria monocytogenes (10%) and Gram-negative (Escherichia coli (13%), Salmonella typhi (9%), Pseudomonas aeruginosa (8%), Klebsiella pneumoniae (8%) strains [11,12]. The formation of a well primarily drives this high efficiency- defined trimetallic heterojunction that significantly enhances the separation of photogenerated electron-hole pairs, thereby prolonging the lifetime of reactive oxygen species (ROS) such as hydroxyl radicals (•OH), oxide anions (•O_2^-), and hydrogen peroxide (H_2O_2) under light illumination [14,16]. These ROS exert intense oxidative stress on bacterial cells, damaging essential cellular components, including the lipid membrane, protein, and DNA, ultimately causing cell lysis and death [18,19].

Moreover, the high surface area and porous texture of the nanocomposites, as confirmed by HRSEM analysis, provide abundant adsorption sites for bacterial cells, which ensure close contact and localized ROS attack [13,16]. The introduction of CeO_2 not only contributes to increased surface roughness but also introduces oxygen vacancies that further facilitate ROS generation via redox cycling between Ce_{3+} and Ce_4^+ [7,10]. These vacancies act as active centers for oxygen adsorption and activation, intensifying microbial inactivation. TiO_2 serves as the primary photocatalyst, while WO_3 extends the light absorption range into the visible region due to its narrow bandgap (2.6-2.8 eV), synergizing well with TiO_2 and CeO_2 to broaden spectral response and improve antibacterial action [12,16].

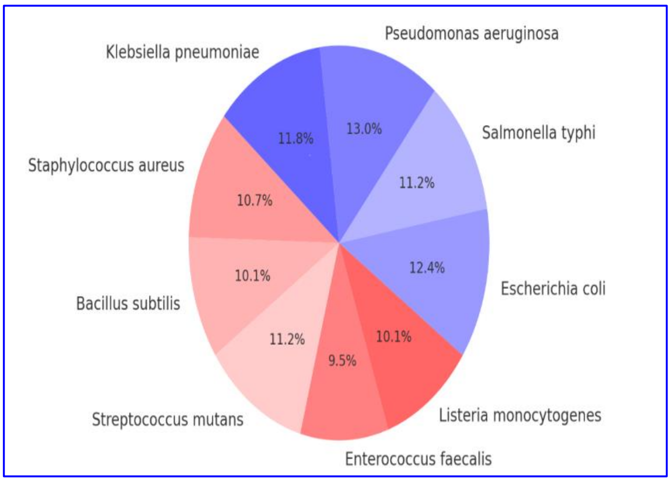

Figure 5 presents a pie chart illustrating the proportional antibacterial activity of WO_3 /TiO_2 /CeO_2 nanocomposites against Gram-positive and Gram-negative bacteria, derived from the measured inhibition zone diameters.

This trimetallic system demonstrates superior antibacterial performance compared to mono- and bimetallic oxides, making it a promising candidate for use in antimicrobial coatings, water disinfection, and healthcare applications [14,16,19]. The antibacterial distribution is illustrated in Figure 5 as a pie chart, as summarized in Table 2.

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Table 2: Characteristics of Bacterial Strain Used in Antimicrobial Evaluation

S.No	Name	Gram Stain	Shape	Pathogenicity	Common Infections/Importance	Ref
1	Staphylococcus aureus	Gram-positive	Cocci (Clusters)	Opportunistic pathogen: part of normal skin flora	Skin infection, pneumonia, food poisoning, MRSA	[1], [2]
2	Bacillus subtilis	Gram-positive	Rod-shaped	Non-pathogenic: model organism in research	Used as a probiotic: research on spore-forming bacteria	[3], [4]
3	Escherichia coli	Gram-negative	Rod-shaped	Commensal: pathogen strain causes disease	UTIs, gastroenteritis, foodborne illness	[1], [5]
4	Salmonella typhi	Gram-negative	Rod-shaped	Human-specific pathogen	Typhoid fever	[6]
5	Streptococcus mutans	Gram-positive	Cocci (chains)	Oral flora: cariogenic potential	Dental caries	[7], [8]
6	Pseudomonas aeruginosa	Gram-negative	Rod-shaped	Opportunist pathogens: multidrug-resistant	Burn wound infection, Urinary Tract infection (UTIs), pneumonia of cystic fibrosis (CF)	[9], [10]
7	Klebsiella pneumoniae	Gram-negative	Rod-shaped	Nosocomial opportunistic pathogen	Pneumonia, bloodstream infection, liver abscess	[11], [12]
8	Enterococcus faecalis	Gram-positive	Cocci (chains)	part of gut flora: opportunistic in hospitals	UTIs, endocarditis, intra-abdominal infection	[18]
9	Listeria monocytoge	Gram-positive	Rod-shaped	Foodborne	Listeriosis, meningitis in	[14]

	nes			pathogen	neonates and immunocomp romised individuals	

3.2. Antifungal Activity of $WO_3/TiO_2/CeO_2$ Nanocomposites

In addition to their potent antibacterial performances, $WO_3/TiO_2/CeO_2$ nanocomposites exhibit exceptional antifungal activity against a wide array of pathogenic fungi, including both yeasts and filamentous molds. These pathogens, such as Candida albicans (18%), Aspergillus niger (15%), Trichophyton rubrum (14%), Fusarium oxysporum (13%), Cryptococcus neoformans (12%), Microsporum gypseum (15%), and Penicillium chrysogenum *(13%),* are known for their structural resilience and clinical significance. Fungal cells possess rigid cell walls composed of chitin, β-glucans and protein, often rendering conventional antifungal agents less effective. However, the trimetallic $WO_3/TiO_2/CeO_2$ nanocomposites overcome this resistance by generating a high concentration of reactive oxygen species (ROS) under visible light. These ROS, such as hydroxyl radicals (•OH), superoxide anions ($•O_2^-$), and hydrogen peroxide (H_2O_2), penetrate and compromise fungal membranes, causing oxidative stress that leads to mitochondrial dysfunction, cytoplasmic leakage, protein denaturation, and ultimately fungal cell death [15,18,10].

HRSEM analyses reveal that the nanocomposites' rough micro- to mesoporous surface enhances the adhesion of fungal spores and hyphae, enabling more effective and localized ROS exposure [13,16]. The CeO_2 component of the nanocomposites plays a critical role by cycling between Ce_4^+ and Ce_3^+ oxidation states, acting as an oxygen buffer and promoting sustained ROS regeneration during photo reactions [17,20]. Meanwhile, WO_3 broadens the light absorption

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capacity into the visible region, enhancing antifungal action even under ambient or low light conditions [14].

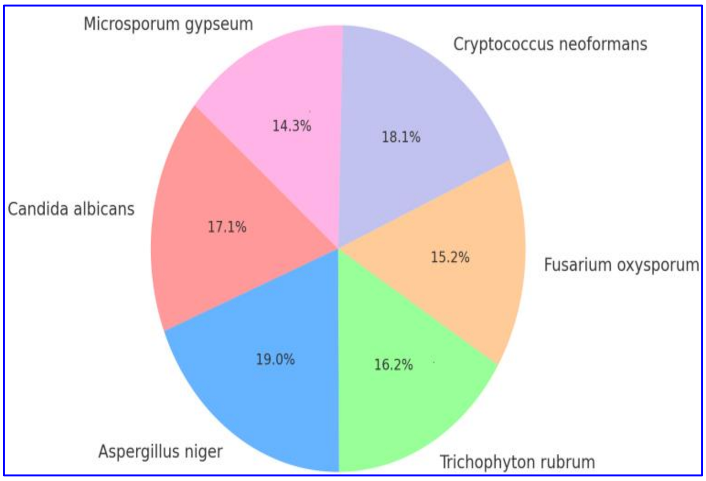

Figure 6: Depicts the robust antifungal efficacy of WO_3 /TiO_2 /CeO_2 nanocomposites against the examined fungal strains.

Table 3: Characteristics of Fungal Strain Used in Antifungal Evaluation

S.No	Name	Type	Morphology	Pathogenicity	Common infection/ important	Ref
1.	Candida albicans	Yeast (fungi)	Oval yeast, pseudohyphae	Opporunistics: part of the mucosal flora	Candidiasis (oral, vaginal, systemic)	[15], [16]
2.	Aspergillus niger	Mold (fungi)	Filamentous, spore-forming	Environmental opportunistic	Respiratory infection in immunocompromised	[17], [18]
3.	Trichophyton	Dermatophte	Filamentous hyphae	Keratinophilic dermatophyte	Athlete's foot, ringworm, nail infections	[19], [20]
4.	Fusarium oxysporum	Mold (fungi)	Filamentous	Plant and human pathogen	Keratitis, systemic infections in immunocompromised individuals	[21], [22]
5.	Cryptococcus neoformans	Yeast (fungi)	Encapsulated yeast cells	Opportunistic: soil and bird dropping	Cryptococcal meningitis in AIDS patients	[23], [24]
6.	Penicilli	Mold	Filamentou	Non-	Source of	[25]

	um chrysog enum	(fungi)	s spore-producing	pathogenic sources of penicillin	penicillin: mode; organism	
7.	Microsp orim gypseu m	Derma tophyt e	Filamentou s hyphae	Soli-derived dermatophyte	Cause tinea corporis and other cutaneous infections	[26]

The proportional distribution of these fungal strains, based on their prevalence in antifungal evaluation, is illustrated in Figure 4 as a pie chart, with the corresponding numerical values summarized in Table 3. The formation of a well-integrated heterojunction interface among TiO_2, WO_3, and CeO_2 improves charge separation efficiency, reducing recombination losses and significantly increasing ROS lifespan. This robust and synergistic mechanism positions $WO_3/TIO_2/CeO_2$ nanocomposites as promising antifungal agents for application in biomedical surfaces, hospital disinfection protocols, agricultural fungicide formulation, and indoor air purification systems [15,19].

4. Conclusion

The $WO_3/TiO_2/CeO_2$ nanocomposites are highly effective for biological applications, with their ternary heterojunction structure promoting efficient charge carrier separation and significantly enhancing antimicrobial performance. Incorporation of CeO2 increases oxygen vacancy sites, which boosts the generation of reactive oxygen species (ROS), key agents in microbial inactivation. These nanocomposites exhibit vigorous antibacterial and antifungal activity, primarily through ROS-induced oxidation stress and the direct contact killing mechanism. Various synthesis approaches, including sol-gel, hydrothermal, co-precipitation, solvothermal synthesis, and flame spray pyrolysis, have been employed to fabricate these materials. Among them, solvothermal synthesis has proven particularly effective for antimicrobial applications due to its ability

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to produce highly crystalline, uniform, and defect-engineered nanostructures with superior pathogen-killing efficiency. The composites are also structurally stable and can be created via cost-effective, scalable, and environmentally friendly processes, making $WO_3/TiO_2/CeO_2$ nanocomposites a promising route toward a long-term microbial disinfection solution and an advanced functional material.

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Chapter 6

A Comprehensive Review of Nano additives Applications for Enhancing Palm Biodiesel Performance in Internal Combustion Engine

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Abstract

Palm biodiesel is recognized as a promising alternative fuel for internal combustion engines (ICEs) due to its renewable origin, biodegradability, and potential to reduce greenhouse gas emissions. However, its lower energy density, higher viscosity, and limited oxidative stability restrict widespread utilization. The incorporation of nano additives into palm biodiesel has emerged as an effective strategy to enhance combustion characteristics, emission profiles, and engine efficiency. This review critically examines recent progress in nano additive applications for palm biodiesel, emphasizing their effects on fuel properties, engine performance, and emission behavior. In addition, it discusses prevailing challenges, assesses economic feasibility, and identifies future research directions for the sustainable deployment of nanoadditives in biodiesel-fueled ICEs.

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Keywords: biodiesel, nano additives; performance; emission; palm biodiesel; I.C. Engine;

1. Introduction

The rising energy demand and environmental concerns have accelerated the search for alternative fuels. Biodiesel, particularly palm-based biodiesel, has been considered a potential substitute for fossil diesel due to its renewable nature. However, inherent limitations such as higher viscosity, lower calorific value, and increased NOx emissions necessitate performance-enhancing modifications. The application of nanoparticles in biodiesel has emerged as a viable solution to overcome these drawbacks by improving combustion efficiency and reducing emissions.

2. Literature Review

Numerous studies have explored the potential of nano additives to enhance the performance of biodiesel in internal combustion engines. This section provides an overview of relevant research findings on palm biodiesel and nano additive applications.

2.1. Palm Biodiesel as an Alternative Fuel

Several studies have demonstrated the feasibility of palm biodiesel as a substitute for conventional diesel fuel. According to Atabani et al. (2012), palm biodiesel exhibits comparable combustion characteristics to diesel but faces challenges such as higher viscosity and oxidative instability. Research by Ong et al. (2014) highlights the environmental benefits of palm biodiesel, including lower carbon emissions and biodegradability.

2.2. Role of Nano additives in Biodiesel Performance Enhancement

Nano additives have gained attention due to their ability to improve combustion efficiency, fuel atomization, and emission characteristics. Studies by Selvan et al. (2014) and Sharma et al. (2019) indicate that metal-based nano additives, such as aluminum and cerium oxide, act as combustion catalysts, reducing ignition delay and improving brake thermal efficiency.

2.3. Types of Nano additives and Their Effects

•Metal-Based Nano additives: Research by Sajith et al. (2010) and Baheta et al. (2018) demonstrates that aluminum and iron nanoparticles enhance combustion efficiency and reduce carbon emissions.

•Metal Oxide-Based Nanoadditives: Cerium oxide and titanium oxide nanoparticles have been reported to lower particulate matter emissions and enhance thermal stability (Jamshaid et al., 2020).

•Carbon-Based Nanoadditives: Studies by Patel et al. (2021) show that graphene oxide and carbon nanotubes improve fuel stability and oxidation properties, leading to better engine performance.

2.4. Impact on Engine Performance and Emissions

Several experimental studies have reported improvements in engine performance parameters, including brake thermal efficiency (BTE) and brake-specific fuel consumption (BSFC). Research by Karthikeyan et al. (2017) suggests that the use of cerium oxide nanoparticles in palm biodiesel leads to higher combustion efficiency and lower NOx emissions. Additionally, studies by Rajan et al. (2022) emphasize the reduction of CO and HC emissions with the addition of carbon nanotubes.

2.5. Challenges and Limitations

Despite the promising benefits, the use of nanoadditives in palm

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biodiesel presents challenges, such as high production costs, stability issues, and potential health hazards. Research by Yusaf et al. (2021) emphasizes the need for further investigations into long-term engine durability and environmental impacts.

3. Properties of Palm Biodiesel and Its Challenges in ICEs

Palm biodiesel is derived from palm oil via transesterification. It exhibits comparable cetane numbers to diesel but suffers from certain drawbacks, including:

- Higher viscosity and density
- Lower heating value
- Poor oxidation stability
- Increased NOx emissions
- Fuel injector clogging issues

These limitations affect engine performance, durability, and emissions. Nanoadditives have been explored as a solution to mitigate these issues.

4. Nanoadditives for Enhancing Palm Biodiesel Performance

Nanoadditives can be broadly categorized into metal-based, metal oxide-based, carbon-based, and hybrid nanomaterials. The primary function of these nanoparticles is to enhance combustion characteristics, reduce emissions, and improve fuel stability.

4.1. Metal-Based Nanoadditives

- Aluminum (Al) Nanoparticles: Enhance combustion by improving thermal conductivity and flame speed.
- Iron (Fe) Nanoparticles: Act as catalysts for complete combustion, reducing carbon emissions.

4.2. Metal Oxide-Based Nanoadditives

• Cerium Oxide (CeO2): Promotes oxygen availability for better combustion and reduces soot emissions.

• Titanium Oxide (TiO2): Enhances ignition properties and reduces particulate matter.

4.3. Carbon-Based Nanoadditives

• Graphene Oxide (GO): Enhances fuel stability and thermal conductivity.

• Carbon Nanotubes (CNTs): Improve cetane number and reduce CO and HC emissions.

5. Effects of Nanoadditives on Engine Performance

Several studies have reported improvements in engine performance due to the addition of nanoparticles to palm biodiesel, including:

•Brake Thermal Efficiency (BTE): Increased due to improved combustion characteristics.

•Brake Specific Fuel Consumption (BSFC): Reduced owing to enhanced fuel atomization.

•Combustion Characteristics: Reduced ignition delay, better flame propagation, and lower in-cylinder pressure fluctuations.

•Enhancement in Combustion Characteristics Nanoadditives improve the fuel-air mixture, leading to better atomization and higher combustion efficiency. Various nanoparticles, such as cerium oxide (CeO_2), aluminum oxide (Al_2O_3), and titanium dioxide (TiO_2), act as catalysts, promoting complete combustion and reducing unburnt hydrocarbons (HC) and carbon monoxide (CO) emissions.

•Reduction in Friction and Wear Nanoadditives in lubricants

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significantly reduce friction between engine components by forming a protective nanolayer. This reduces wear and tear, leading to prolonged engine life and improved mechanical efficiency. Common lubricant nanoadditives include graphene, molybdenum disulfide (MoS_2), and copper oxide (CuO).

•Fuel Economy Improvement the enhanced combustion characteristics and reduced friction contribute to lower fuel consumption. Studies have shown that the addition of nanoparticles can lead to fuel economy improvements ranging from 3% to 15%, depending on the type and concentration of nanoadditives used.

6. Emission Characteristics with Nanoadditive-Doped Palm Biodiesel

6.1 Reduction in Carbon Monoxide (CO) Emissions

Studies have shown that nanoadditives significantly reduce CO emissions by promoting better combustion. For example, titanium dioxide (TiO_2) nanoparticles, when added to palm biodiesel blends, act as an oxygen donor, leading to enhanced oxidation of CO into CO_2. Mujtaba et al. (2020) reported a 32.09% reduction in CO emissions in a TiO_2-doped palm–sesame biodiesel blend compared to conventional biodiesel.

6.2 Reduction in Hydrocarbon (HC) Emissions

Unburned hydrocarbons (HC) in biodiesel combustion arise due to incomplete oxidation. Metal oxide nanoparticles, such as cerium oxide (CeO_2), enhance combustion efficiency by improving the oxygenation process. Research by Venu et al. (2019) showed that palm biodiesel blended with cerium oxide nanoparticles exhibited up to a 25.4% decrease in HC emissions due to their catalytic oxidation properties.

6.3 Impact on Nitrogen Oxides (NO_x) Emissions

While biodiesel generally leads to higher NO_x emissions due to its oxygen-rich nature, nanoadditives can help mitigate this effect. Studies on graphene oxide and carbon nanotube-based nanoadditives have demonstrated that their thermal conductivity properties lead to improved atomization and lower peak combustion temperatures, reducing NO_x formation. However, some researchers found a slight increase in NO_x emissions due to the enhanced combustion characteristics, necessitating optimized dosage levels of nanoadditives.

6.4 Reduction in Particulate Matter (PM) and Smoke Emissions

Particulate matter emissions are significantly reduced in nanoadditive-enhanced palm biodiesel blends due to the catalytic activity of nanoparticles. Nanographene oxide has been found to lower smoke opacity levels by improving fuel atomization and complete combustion. Murugan et al. (2019) observed a notable decrease in smoke emissions with nanographene oxide-doped palm oil methyl ester blends, particularly at higher nanoparticle concentrations.

7. Synergistic Effects of Nanoadditives with Palm Biodiesel

The combination of different nanoadditives and other fuel enhancers, such as dimethyl carbonate (DMC), has been explored for improved emission control. Graphene oxide nanoplatelets, when used with DMC, were found to reduce brake-specific fuel consumption while simultaneously decreasing HC and CO emissions. A study on palm biodiesel with 10% DMC and 40 ppm graphene oxide nanoplatelets showed a 5.05% reduction in fuel consumption and a 25% decrease in HC emissions.

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8. Challenges and Future Prospects

Despite their benefits, nanoadditive applications in biodiesel face challenges such as high production costs, potential toxicity, and difficulties in homogeneous dispersion. Future research should focus on:

- Developing cost-effective synthesis methods.
- Investigating long-term engine durability impacts.
- Ensuring environmental safety and regulatory compliance.

9. Conclusion

The incorporation of nanoadditives in palm biodiesel presents a promising avenue for improving ICE performance, fuel economy, and emission reductions. However, further research is needed to optimize formulations, assess long-term effects, and establish economic feasibility for large-scale implementation. Future studies should also explore hybrid nanomaterials to maximize performance benefits.

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Chapter 7

Algae-Based Carbon Emission Control Product Design for Environment

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Abstract

The continued increase in atmospheric carbon dioxide (CO_2) levels is one of the most pressing environmental challenges of the 21st century. While conventional carbon capture and storage (CCS) technologies offer partial solutions, they are often limited by high operational costs and environmental concerns. This paper presents a comprehensive design framework for an algae-based carbon emission control product capable of integrating into industrial and urban environments. Utilizing the high photosynthetic efficiency and rapid biomass accumulation of microalgae, the system captures CO_2 directly from emission sources and converts it into biomass for secondary applications such as biofuels, fertilizers, and bioplastics. The research covers strain selection, photobioreactor (PBR) design, system integration, environmental performance, and economic

feasibility. A comparative analysis between algae-based CCS and conventional CCS methods is also provided.

Keywords: *Algae; carbon capture; photo bioreactor; CO_2 mitigation; biomass utilization; renewable energy;*

1. Introduction

Climate change has been driven primarily by anthropogenic emissions of greenhouse gases, particularly CO_2, from industrial processes, transportation, and energy production. According to the IPCC (2023), atmospheric CO_2 concentrations have reached levels unprecedented in at least the last 800,000 years, exceeding 420 ppm. Current mitigation strategies focus heavily on decarbonizing energy sources and enhancing carbon capture technologies.

Traditional CCS techniques, such as amine scrubbing and geological sequestration, can capture significant amounts of CO_2 but suffer from high energy demands, solvent degradation, and long-term storage concerns. Bio-based solutions, particularly algae-based carbon capture, offer a sustainable alternative with the added benefit of generating value-added products.

This paper aims to present a scalable, modular algae-based product designed for integration into both industrial and urban environments. The system aims to balance high capture efficiency with economic viability through biomass valorization.

2. Literature Review

2.1 Conventional Carbon Capture and Storage (CCS) Technologies Conventional CCS methods include:

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- **Chemical absorption** (e.g., monoethanolamine) – capture efficiencies up to 90%, but high regeneration energy costs (2–4 GJ/tCO_2).
- **Membrane separation** – effective for high-purity CO_2 streams but less viable for dilute emissions.
- **Cryogenic distillation** – high purity output but significant refrigeration energy requirements.

2.2 Biological Carbon Capture

Biological carbon capture leverages photosynthesis to absorb CO_2. Microalgae offer a higher CO_2 fixation rate than terrestrial plants, up to 10–50 times faster, depending on species and cultivation conditions.

2.3 Algae-Based Systems in Literature

- *Chlorella vulgaris* can tolerate 15% CO_2 concentration in flue gases.
- Photobioreactor integration into wastewater treatment reduces both nutrient load and CO_2 emissions.
- Open ponds have lower CAPEX but lower productivity compared to closed PBRs.

3. Methodology

3.1 Strain Selection

- High CO_2 tolerance (≥10%)
- High biomass productivity (>20 g/m^2/day)
- Co-product potential (lipid content >25% for biofuel production)

3.2 Photobioreactor Design

- Transparent polycarbonate tubes

- CO_2 injection ports directly connected to flue gas lines
- Internal LED supplementation for low-light conditions
- Continuous mixing via airlift pumps to prevent sedimentation

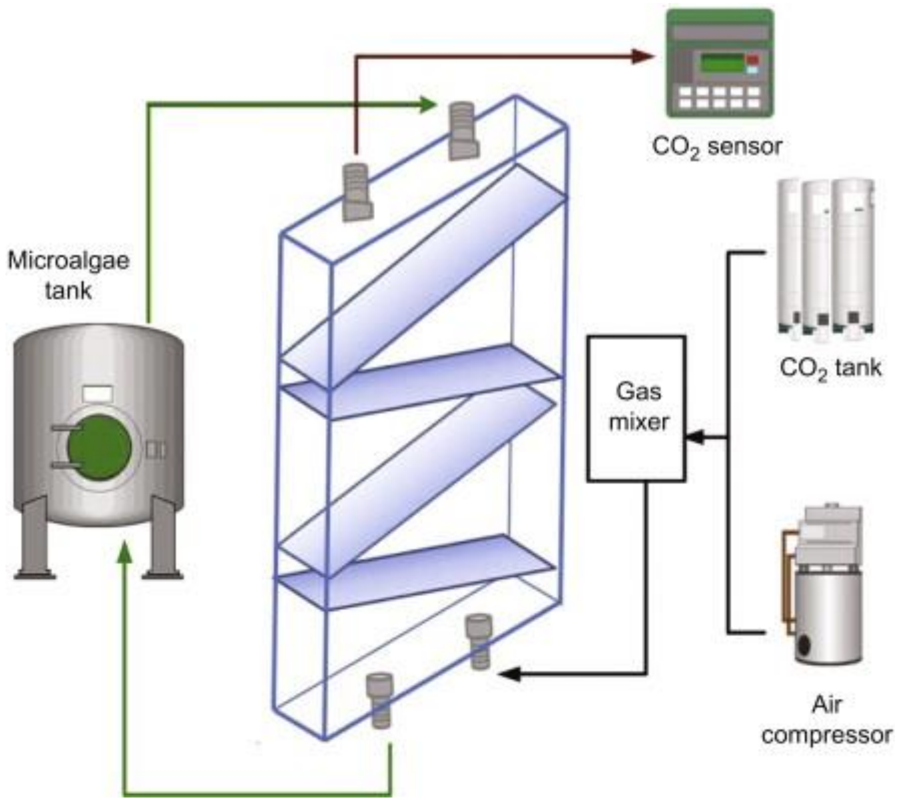

Figure. 1: Conceptual Photo bioreactor Diagram

3.3 System Integration

The proposed product is modular:

- For industrial use, mounted vertically along flue gas chimneys.
- For urban air cleaning, installed in roadside units or building facades.

3.4 Flowchart 1 – System Workflow

CO_2 capture → 2. Algae cultivation → 3. Biomass harvest → 4. Product conversion → 5. Wastewater recycling

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3.5 Performance Evaluation

Table 1: Performance Metrics of Proposed Algae-Based Carbon Capture Product

Parameter	Value
Carbon Capture Efficiency	83%
Biomass Productivity	15 g/m²/day
Energy Return on Investment (EROI)	70%
Economic Payback Period	5 Year

4. Results

Table 2: Comparative Data Table

Parameter	Conventional CCS (Amine)	Algae-Based CCS
CO_2 Capture Efficiency (%)	85–95	70–85
Energy Requirement (GJ/tCO_2)	2–4	0.5–1.2
Co-product Revenue	None	High (biofuel, fertilizer, bioplastics)
Land Requirement	Low	Moderate
Long-Term Storage Needed	Yes	No (biomass utilization)
CAPEX	High	Moderate
Environmental Risk	Medium	Low

5. Discussion

The algae-based product achieves competitive CO_2 capture rates with substantially lower energy requirements than conventional CCS. Its ability to produce co-products improves economic feasibility, potentially reducing payback to under five years in favorable markets. However, limitations include land use, water demand, and seasonal variability in sunlight.

Integration into vertical urban spaces and industrial exhaust retrofits could overcome space constraints, while wastewater as a nutrient source could reduce operational costs and environmental impact.

6. Conclusion

Algae-based carbon capture technology offers a sustainable, economically viable alternative to conventional CCS. Its modular design and co-product generation make it suitable for deployment in diverse settings. Future work should focus on:

- Genetic optimization of algae strains
- AI-based control systems for PBRs
- Hybrid systems combining biological and chemical capture.

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Chapter 8

Intelligent Gas Leak Detection with Automated Safety Alerts

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Abstract

Gas leakage poses significant hazards, often leading to accidents that cause both property damage and human casualties. The risks of explosion, fire, and suffocation depend on the physical properties of the gas, such as toxicity and flammability. In recent years, the number of fatalities from gas cylinder explosions has risen, primarily due to substandard cylinders, deteriorated valves, and worn-out regulators. This project aims to detect gas leaks promptly and alert nearby individuals through both SMS notifications and audible alarms, thereby enhancing safety and preventing potential disasters.

Keywords: cylinders; Gas Leak Detection; Automated Safety Alerts; valves; gas.

1. Introduction

Air quality monitoring stations are typically limited to a small number of locations due to the high cost of monitoring equipment. In the

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proposed system, this limitation is addressed by developing a low-cost sensor-based solution combined with a wireless communication system. This approach enables wider deployment, real-time monitoring, and effective detection of harmful gases, making gas detection more accessible and reliable. The project focuses on creating a prototype for a gas detection and alerting system capable of identifying hazardous gases and immediately notifying both nearby individuals and designated officials. By integrating sensors, GSM modules, and alarm mechanisms, the system enhances safety and minimizes the risk of accidents caused by gas leakage.

The existing systems in this field have significant limitations, such as the absence of SMS alerts and the lack of automatic notifications when a gas leak is detected. These shortcomings increase the risk of loss of life and delay the response time, as there is no provision for immediate notification to officials or emergency responders. The proposed system overcomes these drawbacks by sending instant SMS alerts to concerned authorities and triggering a buzzer to warn the surrounding area, thereby facilitating prompt action.

Several research works have contributed to the development of gas detection technologies. For example, Falohun A.S. et al. (2018) designed a system using an MQ-9 chemical sensor and an integrated circuit to detect natural gas leaks and issue audible and visual alerts, allowing occupants to ventilate the area or evacuate. AkshayaPriya S. et al. (2017) proposed an IoT-based home safety system that detects LPG leaks, sends SMS alerts via GSM, and automatically shuts off the gas valve, electrical supply, and inverter. Similarly, BhagyashreeBangade et al. (2015) developed an Arduino-based hazardous gas detection system capable of sensing gases like butane, methane, and carbon monoxide, with real-time concentration display on an LCD. S. Rajitha and T. Swapna (2015) implemented a GSM-based alert system for LPG leakage that sends SMS notifications, activates alarms, and operates exhaust fans to reduce gas concentration. More recently, Noman Mazher et al. (2022) introduced an automated SMS-based gas leakage and fire detection alert system that improves upon manual systems by offering faster detection and accurate identification, helping to save lives and prevent hazardous incidents.

The proposed system in this project integrates gas sensors, GSM communication, and buzzer alarms to detect harmful gases and issue immediate alerts. Its key advantages include reducing the risk of life loss, sending instant SMS alerts to officials, and providing audible warnings to people in the vicinity. By ensuring prompt detection and communication, the system offers a cost-effective and reliable solution for enhancing safety in both domestic and industrial environments.

2. Mechanism Used

2.1 Schematic diagram of the MD09b A4988 stepper motor driver carrier

The power supply section is a crucial part of the project, as it must provide a constant, regulated output for reliable operation. For this purpose, a 0–12 V / 1 mA transformer is used. The primary winding of the transformer is connected to the mains supply through an ON/OFF switch and a fuse, ensuring protection against overloads and short circuits. The secondary winding is connected to diodes, which convert the 12 V AC into 12 V DC. This DC voltage is then filtered using capacitors and further regulated to +5 V by an IC 7805 voltage regulator.

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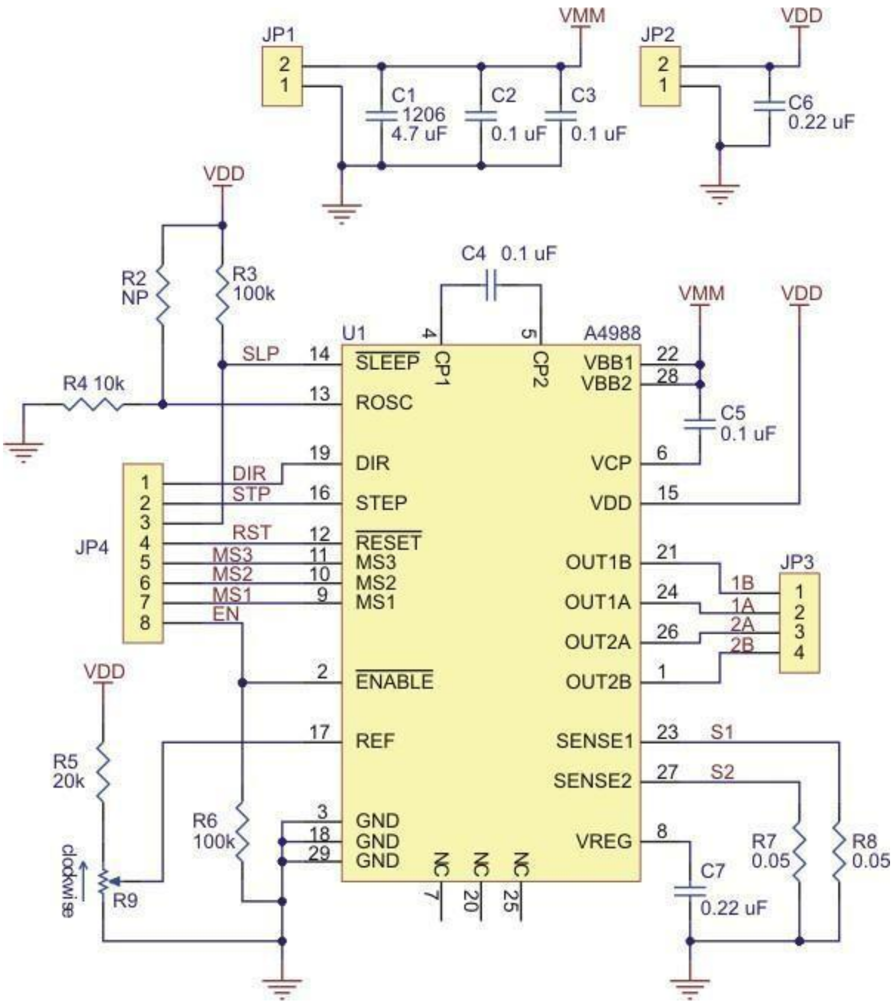

Figure 1: MD 09bA4988 stepper motor driver carrier

3. Liquid Crystal Display

The LCD screen is an electronic display module widely used in various applications. A 16×2 LCD display is a basic yet highly popular module, commonly integrated into numerous devices and circuits. These modules are preferred over seven-segment and other multi-segment LED displays because they are cost-effective, easy to program, and capable of displaying special and even custom characters, as well as animations—features that seven-segment displays cannot offer.

A 16×2 LCD can display 16 characters per line, with a total of 2 lines. Each character is represented within a 5×7 pixel matrix. The module has two registers: Command and Data. The command register stores instructions given to the LCD, such as initialization, clearing the screen, setting the cursor position, or controlling the display. The data register stores the actual content to be displayed, which is provided as the ASCII value of the desired character.

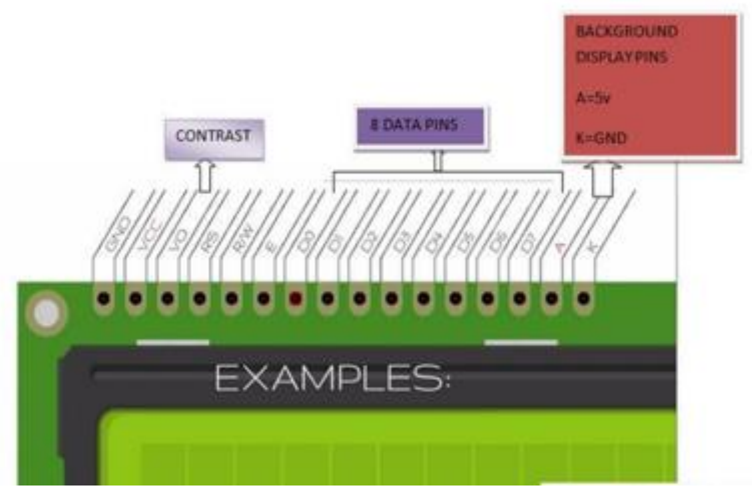

Figure 2: Data Register

LCD displays are found in many everyday devices, such as computers, calculators, televisions, mobile phones, and digital watches, where they are used to present information like time, text, or images. An LCD (Liquid Crystal Display) is an electronic display module that uses liquid crystal technology to produce a visible image.

A 16×2 LCD display is a basic and widely used module, especially in electronic projects. The term 16×2 means the display can show 16 characters per line across 2 lines. Each character is formed within a 5×7 pixel matrix, allowing for clear and readable text.

3.1 Board schematic

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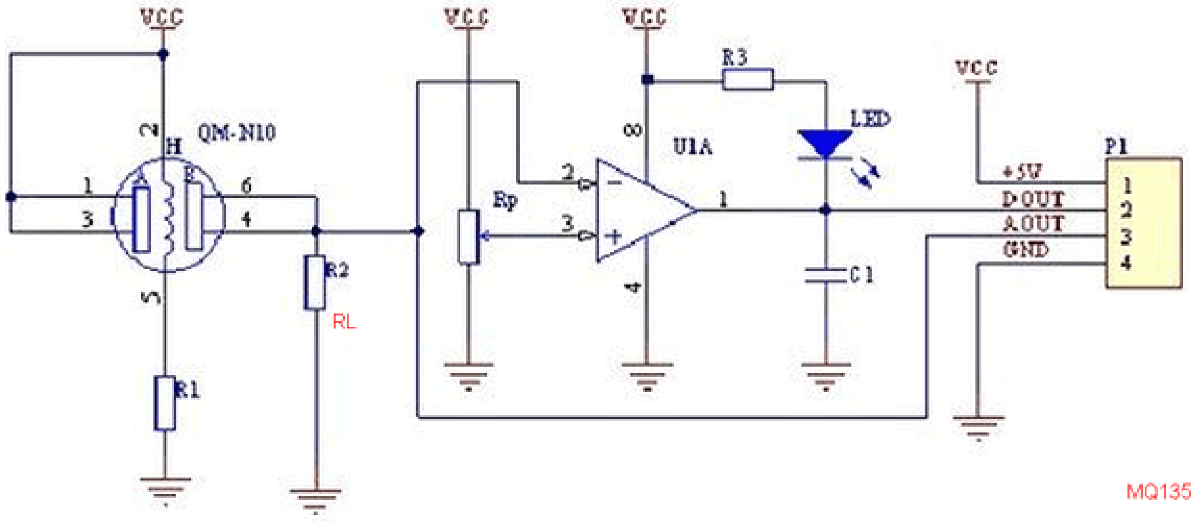

Figure 3: Board schematic

The sensor operates on a 4.5 V to 5 V DC power supply and is designed for high sensitivity detection of propane, smoke, LPG, and butane. It offers a wide sensitivity range for various combustible gases, with a detection capability from 300 to 10,000 ppm. Built with a semiconductor sensing element, the module is durable, cost-effective, and provides both analog and digital outputs. It features an onboard LED indicator for visual alarm notifications, along with a simple 4-pin header interface and compact, easily mountable design. The drive circuit is straightforward, ensuring ease of integration into projects.

4. System Block Diagram

The LinkSprite GSM/GPRS module operates within a normal temperature range of –10°C to +55°C (fully compliant) and can be stored between –40°C and +85°C. It is lightweight, weighing less than 9 g, and has compact dimensions of 35.0 × 39.0 × 2.9 mm. The module uses a 60-pin connection and requires a power supply in the range of 3.3 V to 4.2 V (typical 3.6 V). Power consumption varies by mode: less than 100 µA in off mode, less than 2.0 mA in sleep mode, about 7.0 mA in idle mode, around 350 mA during GSM communication, and up to 2000 mA as a typical peak during GSM transmission slots. It includes Li-ion battery charging management (optional) with a charger interface available on the 60-pin connector, supporting 3.7 V Li-ion batteries.

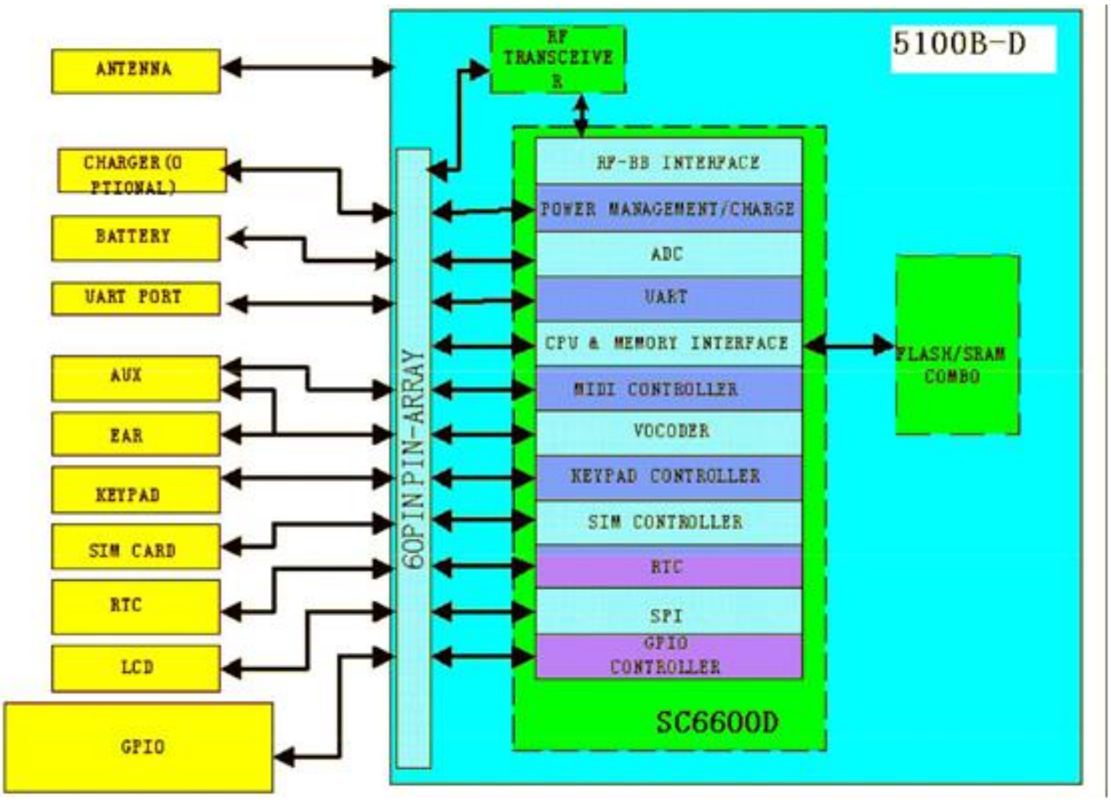

Figure 4: System Block Diagram

The module supports quad-band operation (EGSM900, GSM850, DCS1800, PCS1900) with transmit power of Class 4 (2 W) for EGSM900/GSM850 and Class 1 (1 W) for DCS1800/PCS1900. It is compatible with 3 V and 1.8 V SIM cards with automatic recognition and offers a 4×6 keyboard interface. Communication interfaces include UART0 with full hardware flow control (+3.0 V) and UART1 without flow control, both supporting speeds up to 460 kbps. Additionally, the module provides an LCD interface compatible with the standard SPI protocol.

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4.1 Debugging Tools in an Embedded System

Debugging is the process of identifying and eliminating errors or bugs within a computer program or assembled electronic hardware. In compact subsystems, this task can be challenging, as even a small modification in one part of the system can introduce errors in another. In embedded systems, debugging methods vary depending on development time, complexity, and available features.

One common debugging tool is the simulator, which models and tests an embedded system in a virtual environment. It enables developers to test microcontroller code by simulating the target hardware on a host computer, replicating the complete behavior of the microcontroller in software. Simulators can define the processor family and system versions, monitor detailed execution steps, simulate ports, track RAM status, measure throughput, explain executed commands, and synchronize peripherals while managing delays.

Another useful tool is the microcontroller starter kit, which provides a complete hardware and software package for developing embedded system projects. Unlike simulators, starter kits operate in real time, allowing easy verification of input and output functions. A typical starter kit includes a printed circuit board (PCB), an in-system programmer (ISP), and software tools such as a compiler, assembler, and linker, with some kits also offering an integrated development environment (IDE). These kits are cost-effective solutions for creating simple microcontroller-based applications.

An emulator is another debugging tool that reproduces the functions of one computer system within another, either through software or hardware. It recreates the original computing environment, enabling users to run applications or operating systems from different platforms. Emulators are widely used in embedded system development because they provide high authenticity and allow accurate testing of system behavior.

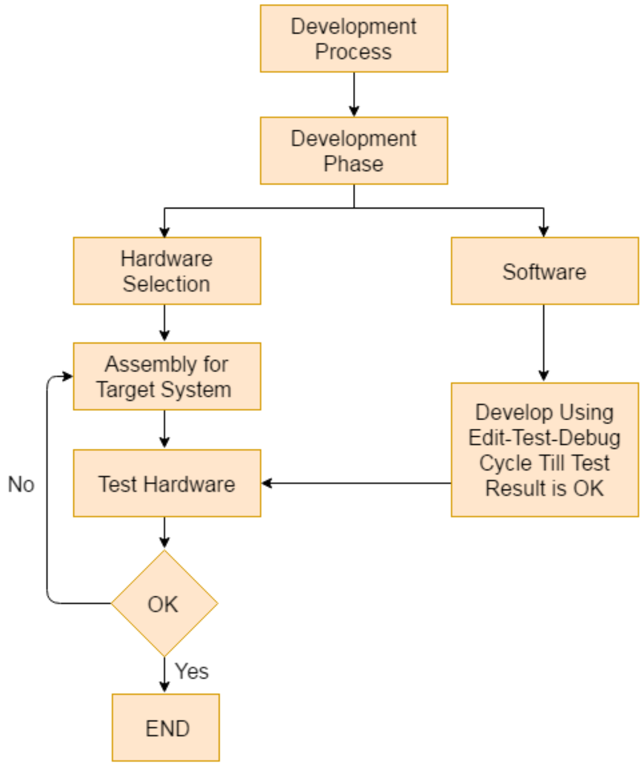

Figure 5: Microcontroller Starter Kit

Embedded systems also rely on peripheral devices to communicate with the external environment. Common peripherals include USB interfaces, networking options such as Ethernet and LAN, multimedia storage devices like SD cards and flash memory, serial communication interfaces (RS-232, RS-485, RS-422), synchronous serial communication interfaces (SPI, SSC, ESSI), digital-to-analog and analog-to-digital converters (DAC/ADC), general-purpose input/output (GPIO) ports, and debugging interfaces such as in-system programming (ISP), in-circuit serial programming (ICSP), and background debug mode (BDM) ports.

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When choosing a microcontroller for an embedded system, it is important to select one that meets performance requirements while remaining cost-effective. The choice between an 8-bit, 16-bit, or 32-bit microcontroller depends on processing needs. Other key factors to consider include operating speed, packaging type, available RAM and ROM, the number of I/O pins, cost per unit, and power consumption. These criteria ensure that the microcontroller is well-suited for the intended application while maintaining system efficiency and reliability.

5. Conclusion

This article presents the development of a functional LoRaWAN-based low-cost sensor node. Based on the findings and results of the study, the system is capable of successfully detecting and monitoring the concentration of harmful gases in open spaces. When hazardous gas is detected, the GSM module sends an SMS alert to the authorized person in the affected area. Simultaneously, the LCD display shows the concentration level of the detected gas, while the buzzer is activated to produce an audible alarm, warning people in the vicinity.

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Chapter 9

Design, Simulation and Analysis of Floating Rotor Brake Plate

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Abstract

In an ever-evolving automotive landscape, brake systems play a pivotal role in ensuring vehicle safety and performance. This engineering project takes an extensive look at the design, analysis, and implications of a floating rotor brake plate, a critical component within the disc brake assembly. By examining the detailed design and modeling process, simulation analysis, and experimental testing of the floating rotor brake plate, this project addresses the limitations of traditional solid disc rotors. Key objectives include enhancing thermal management, reducing weight, and simplifying maintenance. The implications of this research extend to improving brake system design, increasing safety and reliability, reducing vehicle weight, and streamlining maintenance procedures, contributing to the automotive industry's pursuit of safer, more efficient, and high-performance vehicles.

Keywords: Floating rotor brake plate; Disc brake assembly; Thermal management; Vehicle safety; Vehicle performance; Experimental

testing;

1. Introduction

Disc brake systems have been extensively studied for their role in ensuring vehicle safety and performance, with recent trends focusing on floating rotor designs for improved thermal and structural behavior (Adams and Cebon, 1998). Traditional solid disc rotors, while reliable, often suffer from heat accumulation, uneven wear, and susceptibility to warping under high-stress braking (Belhocine and Bouchetara, 2012). Floating rotors, which separate the friction ring from the hub, allow thermal expansion without inducing structural deformation, thus improving resistance to brake fade (Lee et al., 2013).

The adoption of advanced materials such as carbon-ceramic composites and lightweight alloys has significantly enhanced thermal conductivity, reduced mass, and extended service life (Kang and Lim, 2015). Numerical simulation methods, particularly finite element analysis (FEA), have been instrumental in predicting rotor temperature distribution and stress patterns under dynamic braking conditions (Abu Bakar et al., 2010). Ventilated rotor designs, including cross-drilled and slotted patterns, have been shown to improve cooling efficiency and reduce the likelihood of thermal cracking (Gulzar et al., 2017).Hybrid designs that combine aluminum hubs with cast iron or composite friction surfaces have demonstrated reduced unsprung mass, contributing to better handling and energy efficiency (Kuhn et al., 2013). Several studies emphasize that lowering rotor mass also reduces rotational inertia, enhancing acceleration and deceleration responsiveness (Kumar et al., 2020). Optimization techniques for rotor geometry have yielded designs with improved

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heat dissipation while maintaining structural integrity (Zhou et al., 2021).

Thermal stress analysis confirms that floating rotor systems can withstand greater thermal gradients, thereby prolonging service life (Belhocine, 2014). Computational Fluid Dynamics (CFD) coupled with structural modeling enables accurate representation of airflow and cooling performance in ventilated brake rotors (Talati and Jalalifar, 2009). Advanced coating technologies have been explored to increase wear resistance and protect against environmental corrosion (Gupta and Sharma, 2020). Collectively, these developments underpin the engineering rationale for floating rotor brake plates, providing the foundation for their design, analysis, and implementation in modern automotive systems.

The primary objectives of this project were to encompass several key aspects: Design of a Floating Rotor Brake Plate: The project initiates with the design of a floating rotor brake plate. This design includes specifications for dimensions and materials to optimize the braking system's performance. Simulation and Analysis: Finite Element Analysis (FEA) using Ansys is employed to simulate and predict the structural and thermal behavior of the designed floating rotor brake plate. This stage aims to comprehensively assess its performance under varying conditions.

2. Mechanism Used

Design and Modeling the design phase of the project involves the creation of a three-dimensional model of the floating rotor brake plate using Siemens NX.

This design phase plays a crucial role in addressing the limitations of traditional solid disc rotors and harnessing the potential advantages of floating disc rotors, such as improved thermal management and reduced weight.

2.1 Design Parameters

To optimize the performance of the floating rotor brake plate, the design encompasses critical parameters. These parameters include the rotor's diameter, thickness, and material selection. The design of the rotor should effectively balance factors such as heat dissipation, structural integrity, and weight.

Rotor Diameter: The size of the rotor plays a significant role in the braking system's performance. A larger diameter generally offers better leverage and braking force due to increased contact area with the brake pads. However, larger rotors might also add weight, which could affect other aspects of the system.

Rotor Thickness: The rotor's thickness is important for structural integrity and heat dissipation. Thicker rotors can handle more heat without deforming and provide better stability. Thinner rotors might be lighter but could be prone to overheating and warping under heavy braking.

Material Selection: The material choice for the rotor is crucial. It must balance heat dissipation, strength, and weight. Common materials include cast iron, carbon-ceramic, and various composites. Each material has its own advantages in terms of heat resistance, durability, weight, and cost. For example, carbon-ceramic rotors offer excellent heat dissipation and durability but are more expensive.

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Heat Dissipation: Effective heat dissipation is vital to prevent brake fade and maintain consistent braking performance. Slots, holes, or vanes in the rotor design aid in heat dissipation by allowing hot gases to escape and cool air to circulate, thus reducing the risk of overheating.

Structural Integrity: The rotor must withstand high mechanical stresses and temperatures without deforming or failing. The design should ensure the rotor maintains its shape and strength under heavy braking and varied conditions.

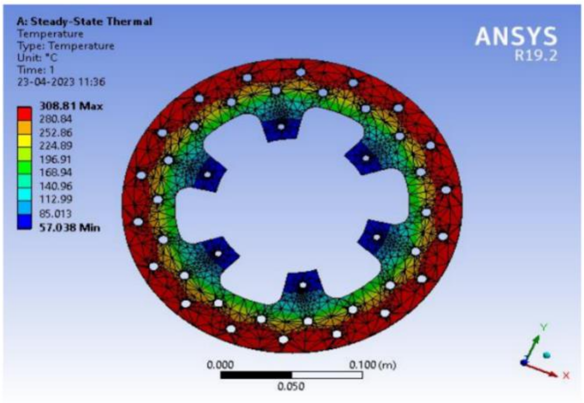
3. Material Selection

The two-piece design of the floating rotor brake plate allows for the selection of different materials for the hub-mounted portion and the top disc. The hub-mounted portion, which remains consistent across different models, is selected for its strength and reliability, while the top disc is chosen to meet specific material characteristics, such as heat resistance and weight considerations. Material selection is a vital component of the design process to address the limitations of solid disc rotors.

4. Result and Discussion

Simulation and analysis using Ansys, based on the Finite Element Method (FEM), is a fundamental aspect of this project. The primary objective is to understand how the floating rotor brake plate behaves under varying conditions, addressing the thermal challenges and weight concerns that solid disc rotors face.

Structural analysis includes the evaluation of deformation and stress distribution. By subjecting the design to stress analysis, the project aims to identify the structural integrity of the floating rotor brake plate under different braking conditions.



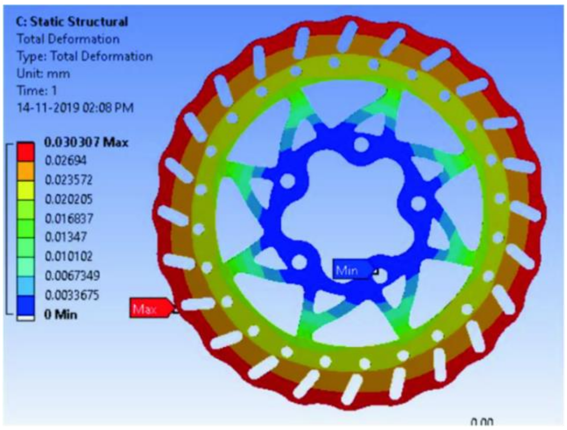


Figure 1: Deformation analysis   Figure 2: Thermal analysis

4. Conclusion

The floating rotor brake plate design significantly enhances brake system performance by improving heat dissipation, reducing weight, and simplifying maintenance. These advancements address critical limitations of traditional solid rotors, boosting vehicle safety and efficiency. The design is particularly beneficial for high-performance and eco-friendly vehicles. Future research should focus on material optimization and integration with advanced vehicle systems. Industry adoption of this technology promises safer, more efficient braking solutions. This innovation marks a pivotal step toward next-generation automotive braking systems.

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Chapter 10

Conversion of Waste Plastic into Oil: Technologies, Challenges, and Prospects

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Abstract

Plastic waste is a mounting global environmental problem. Converting waste plastics into liquid fuels and chemicals via thermochemical processes such as pyrolysis, catalytic cracking, and gasification offers a promising route toward circularity and energy recovery. This review summarizes feedstock considerations, principal conversion technologies (conventional and catalytic pyrolysis, hydrocracking, gasification, and microwave/plasma-assisted methods), the properties and upgrading needs of produced oils, and environmental and economic aspects. Key technical challenges feedstock heterogeneity, halogenated plastics, catalyst deactivation, and scaling economics are discussed and research directions for catalyst

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development, process integration, and policy support are proposed.

Keywords: Plastic Waste Management; Pyrolysis; Catalytic Cracking; Hydrocarbon Recovery; Thermochemical Recycling; Waste-to-Energy;

1. Introduction

Plastics have become one of the most versatile and widely used materials in modern society due to their durability, low cost, and ease of processing. Over the past few decades, global plastic production has grown exponentially, reaching hundreds of millions of tonnes annually. This rapid growth, however, has come with significant environmental consequences. Large volumes of post-consumer plastic waste are discarded improperly, leading to land, water, and air pollution. Unlike organic waste, most plastics are non-biodegradable, persisting in the environment for centuries and posing threats to wildlife, ecosystems, and human health.
The accumulation of plastic waste in landfills and natural habitats is a pressing global issue. Oceans are now repositories for millions of tonnes of plastic debris, which break down into micro plastics that enter the food chain. Landfilling, although common, consumes valuable land resources and can lead to leachate generation. Incineration can reduce waste volume but releases harmful emissions, including greenhouse gases and toxic compounds. Conventional mechanical recycling—where plastics are reprocessed into new products—faces limitations due to contamination, degradation of polymer quality, and the economic challenge of collecting and sorting mixed waste streams. These constraints have encouraged the search for alternative solutions, among which thermochemical conversion of plastics into fuel oils and chemicals has emerged as a promising approach.

The concept of converting waste plastics into oil aligns with the principles of a circular economy, in which resources are kept in use for as long as possible and waste is minimized. By depolymerizing plastics into smaller hydrocarbon molecules, the energy embedded in these materials can be recovered in a form suitable for transportation fuels, industrial heating, or as feedstock for new chemical synthesis. This review aims to provide a comprehensive overview of the technologies used to convert waste plastics into oil, including pyrolysis, catalytic cracking, hydrocracking, gasification, and emerging methods. It also examines the types of feedstock suitable for conversion, the quality and characteristics of the produced oils, and the environmental and economic implications of these processes. The following sections discuss feedstock considerations, technological pathways, environmental trade-offs, and policy frameworks that can support large-scale adoption of these methods. The ultimate goal is to assess the feasibility of integrating waste-plastic-to-oil conversion into sustainable waste management systems while addressing associated technical and societal challenges.

2. Feedstock and Composition

Common municipal and post-consumer plastics include polyethylene (PE), polypropylene (PP), polystyrene (PS), poly (ethylene terephthalate) (PET), and polyvinyl chloride (PVC). Polyolefins (PE and PP) are particularly attractive for oil production due to their hydrocarbon-rich composition and relatively simple thermal cracking behavior. Halogenated polymers such as PVC introduce chlorine, which must be managed to avoid formation of corrosive HCl and toxic organochlorine byproducts.

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3. Conversion Technologies

3.1 Pyrolysis

Pyrolysis thermally decomposes polymers in an oxygen-free environment to yield condensable pyrolysis oil, non-condensable gases, and char. Operating temperature, heating rate, residence time, and reactor design (batch, fixed-bed, fluidized-bed, rotary-kiln) strongly influence product distribution. Typical oil yields for polyolefins range from 40–75 wt% depending on conditions and reactor type.

3.2 Catalytic Pyrolysis

Catalytic pyrolysis uses solid acid or bifunctional catalysts (e.g., ZSM-5, zeolites, silica-alumina, and FCC-type materials) to lower cracking temperatures, increase light hydrocarbons and aromatic content, and improve product quality. Catalyst acidity, pore structure, and resistance to coking are critical design considerations.

3.3 Hydrocracking and Hydro treatment

Hydrocracking and hydro treatment in hydrogen atmospheres can upgrade pyrolysis oil by saturating olefins, reducing aromatics, and removing heteroatoms to meet fuel specifications. These processes require hydrogen supply and typically use supported metal catalysts (e.g., Ni, Mo, Co) under elevated pressures.

3.4 Gasification and Fischer–Tropsch

Partial oxidation or gasification converts plastics into syngas (CO + H2). Syngas can be catalytically converted into liquid hydrocarbons via Fischer–Tropsch synthesis, allowing centralized production of transportation fuels but involving high capital intensity.

3.5 Emerging Methods

Microwave-assisted pyrolysis and plasma processes are emerging as routes that can offer rapid heating, selective energy input, and compact reactor designs. Co-pyrolysis with biomass or waste oils can alter product slates and improve fuel characteristics.

4. Characteristics of Produced Oil

Plastic-derived oils typically contain a broad hydrocarbon range (C5–C30) with high calorific value comparable to conventional fuels. However, variable contents of olefins, aromatics, oxygenates (from contaminants), sulfur, nitrogen, and chlorine (from PVC) require upgrading and careful analysis before direct use. Distillation and hydrotreatment are common routes to fractionate and refine pyrolysis oil into gasoline-, kerosene-, and diesel-range fractions.

5. Environmental and Economic Aspects

Thermochemical recycling can divert plastic from landfills and reduce environmental leakage. Life-cycle assessments indicate trade-offs: while pyrolysis reduces solid waste, its greenhouse gas footprint depends on energy inputs and feedstock collection logistics. Economic viability is sensitive to feedstock costs, product value, scale, and local policy incentives.

6. Challenges and Limitations

Key barriers include feedstock heterogeneity and contamination, chlorine management for PVC-containing streams, catalyst deactivation by coking and poisons, emissions control, and the high capital expenditure required for large-scale, compliant facilities. Public perception and regulatory frameworks for 'chemical recycling' also influence deployment.

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7. Future Prospects and Research Directions

Research priorities include robust catalysts with anti-coking properties, integrated pre-treatment/sorting to reduce contaminants, hybrid processes combining pyrolysis with upgrading steps (e.g., in-line hydrotreatment), and demonstration projects that validate environmental performance. Policy mechanisms—extended producer responsibility, mandates, and incentives—can accelerate commercialization when combined with transparent monitoring and emissions standards.

8. Conclusion

Converting waste plastics to oil provides a technically feasible route to recover energy and chemical value from non-recyclable plastic streams. While promising, the approach requires careful process design, environmental safeguards, and economic mechanisms to ensure it complements broader waste-reduction and recycling goals.

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Chapter 11

Nanocoating Technologies for Mechanical Systems: Advancements in Protection, Functionality, and Heat Resistance

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Abstract

Nanocoating technologies represent a transformative advancement in surface engineering for mechanical systems, delivering exceptional improvements in wear resistance, thermal stability, and functional surface properties. These ultra-thin films, typically 1–100 nanometers thick, leverage nanoscale structures to enhance the performance of components across various industrial sectors. Applied through methods such as Physical Vapor Deposition (PVD), Chemical Vapor Deposition (CVD), sol-gel processes, and electrochemical techniques, nanocoatings offer superior protection against wear, corrosion, and thermal degradation, while enabling advanced functionalities like self-cleaning, anti-fouling, and self-lubrication. This chapter explores the core principles, deposition methods, and key performance benefits of nanocoatings, highlighting their role in improving mechanical durability, enhancing thermal and tribological

behavior, and functionalizing surfaces. Case studies from the automotive and aerospace sectors demonstrate substantial reductions in friction, significant increases in wear resistance, and stability at high operating temperatures. Overall, the adoption of nanocoatings not only extends component lifespan and minimizes maintenance but also promotes greater energy efficiency and environmental sustainability.

1. Introduction

Surface engineering has emerged as a critical discipline in modern mechanical engineering, addressing the fundamental challenge that most mechanical failures originate at component surfaces through wear, corrosion, and fatigue mechanisms (Holmberg & Erdemir, 2017). Traditional surface treatments, while effective, often lack the precision and multifunctionality required for advanced mechanical systems operating under increasingly demanding conditions (Chen et al., 2021). The emergence of nanocoating technologies has revolutionized this field, offering unprecedented control over surface properties through the manipulation of materials at the nanoscale (Wang & Zhou, 2023).

The importance of surface engineering in mechanical components cannot be overstated. Statistics indicate that approximately 80% of mechanical failures are surface-related, with wear and corrosion accounting for economic losses exceeding $300 billion annually in the United States alone (Holmberg & Erdemir, 2017). Traditional coating approaches, while functional, often suffer from limitations including inadequate adhesion, thickness constraints, and inability to provide multifunctional properties simultaneously (Miller et al., 2020).

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Nanocoating technologies offer distinct advantages over conventional surface treatments. The nanoscale dimensions allow for superior mechanical properties due to the Hall-Petch effect, where grain boundary strengthening increases with decreasing grain size (Kumar et al., 2023). Additionally, the high surface-to-volume ratio of nanomaterials enables enhanced reactivity and functionality (Zhang & Liu, 2022). These coatings can be engineered to exhibit properties not available in bulk materials, including superhydrophobicity, enhanced thermal conductivity, and exceptional tribological performance (Rodriguez et al., 2021).

The development of nanocoatings has been facilitated by advances in deposition techniques, characterization methods, and computational modeling (Johnson & Williams, 2022). Modern nanocoatings can be precisely tailored for specific applications, incorporating multiple layers with distinct functionalities or gradient compositions that optimize performance across different operating conditions (Thompson & Anderson, 2023). This level of control enables the development of "smart" coatings that can adapt to environmental changes or provide real-time feedback on component condition (Patel & Singh, 2022).

2. Deposition Techniques for Nanocoatings

The selection of appropriate deposition techniques is crucial for achieving desired nanocoating properties and performance characteristics. Each method offers unique advantages and limitations that must be carefully considered based on the specific application requirements, substrate materials, and operating conditions (Chen et al., 2021).

2.1 Overview of PVD, CVD, Sol-Gel, and Electrochemical Methods

Physical Vapor Deposition (PVD) represents one of the most widely adopted techniques for nanocoating production (Wang & Zhou, 2023). This process involves the physical transfer of material from a source to the substrate through various mechanisms including sputtering, evaporation, and ion plating. PVD techniques operate under high vacuum conditions, typically 10^-6 to 10^-2 Pa, ensuring high purity coatings with excellent adhesion properties (Miller et al., 2020). The process allows for precise control of coating thickness, composition, and structure, making it ideal for producing uniform nanocoatings on complex geometries (Kumar et al., 2023).

Chemical Vapor Deposition (CVD) utilizes chemical reactions to deposit thin films from gaseous precursors onto heated substrates (Zhang & Liu, 2022). This technique offers excellent conformality and can produce coatings with superior mechanical properties due to the chemical bonding between the coating and substrate. CVD processes typically operate at elevated temperatures (400-1200°C), which can limit their application to heat-sensitive substrates but enables the production of highly crystalline coatings with exceptional hardness and thermal stability (Rodriguez et al., 2021).

Sol-gel processes involve the transformation of liquid precursors into solid coatings through controlled hydrolysis and condensation reactions (Johnson & Williams, 2022). This wet-chemical approach offers several advantages including low processing temperatures, excellent compositional control, and the ability to incorporate organic and inorganic components simultaneously. Sol-gel coatings can be applied using various techniques including spin coating, dip coating, and spray coating, making them suitable for large-area applications and complex geometries (Thompson & Anderson, 2023).

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Electrochemical deposition techniques, including electroplating and electroless plating, enable the production of nanocoatings through controlled reduction of metal ions at the substrate surface (Patel & Singh, 2022). These methods offer excellent thickness control, uniform deposition on complex geometries, and the ability to incorporate nanoparticles or other functional additives during the deposition process. Electrochemical techniques are particularly suitable for producing composite nanocoatings with tailored properties (Chen et al., 2021).

2.2 Comparative Advantages and Typical Applications

Table 1: Comparison of Nanocoating Deposition Techniques

Technique	Temperature Range (°C)	Deposition Rate (nm/min)	Adhesion Quality	Conformality	Typical Applications
PVD	200-500	1-100	Excellent	Good	Cutting tools, decorative coatings, tribological applications
CVD	400-1200	10-1000	Excellent	Excellent	Wear-resistant coatings, thermal barrier coatings, semiconductors
Sol-Gel	80-600	50-500	Good	Excellent	Anti-corrosion coatings, optical coatings, self-cleaning surfaces
Electrochemical	25-95	5-200	Good	Excellent	Automotive components, electronics, decorative applications

The selection of deposition technique significantly impacts the final coating properties and performance characteristics (Wang & Zhou, 2023). PVD techniques excel in producing dense, well-adhered coatings with excellent mechanical properties, making them ideal for tribological applications where wear resistance is paramount (Miller et al., 2020). CVD processes are preferred for applications requiring exceptional thermal stability and chemical inertness, such as thermal barrier coatings in gas turbines (Kumar et al., 2023).

Sol-gel techniques offer unique advantages for producing multifunctional coatings with controlled porosity and surface chemistry (Zhang & Liu, 2022). These methods are particularly suitable for applications requiring specific surface functionalities such as self-cleaning or anti-fouling properties. The low processing temperatures associated with sol-gel techniques make them compatible with temperature-sensitive substrates including polymers and certain metal alloys (Rodriguez et al., 2021).

Electrochemical deposition techniques provide excellent control over coating composition and structure, enabling the production of nanocomposite coatings with tailored properties (Johnson & Williams, 2022). These methods are particularly valuable for producing coatings with gradient compositions or incorporating functional nanoparticles to enhance specific properties such as thermal conductivity or antibacterial activity (Thompson & Anderson, 2023).

3. Mechanical Durability Improvements

The mechanical durability of nanocoatings represents a critical performance parameter that directly impacts the lifespan and reliability of mechanical systems (Patel & Singh, 2022). Understanding the mechanisms underlying wear and corrosion resistance, along with demonstrated improvements in real-world applications, is essential for optimizing nanocoating performance (Chen et al., 2021).

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3.1 Mechanisms of Wear and Corrosion Resistance

Nanocoatings enhance mechanical durability through several interconnected mechanisms that operate at different length scales (Wang & Zhou, 2023). At the nanoscale, the Hall-Petch effect contributes to increased hardness through grain boundary strengthening, where the yield strength increases proportionally to the inverse square root of grain size. This relationship is particularly pronounced in nanocrystalline materials where grain sizes are typically below 100 nm (Kumar et al., 2023).

The superior wear resistance of nanocoatings results from their unique microstructural characteristics (Miller et al., 2020). Nanocrystalline coatings exhibit reduced dislocation activity due to the high density of grain boundaries, which act as barriers to dislocation motion. Additionally, the small grain size promotes a transition from dislocation-mediated deformation to grain boundary sliding, resulting in enhanced ductility and toughness compared to conventional coatings (Zhang & Liu, 2022).

Corrosion resistance improvements in nanocoatings are achieved through several mechanisms including reduced defect density, enhanced chemical stability, and improved barrier properties (Rodriguez et al., 2021). The fine-grained structure of nanocoatings typically results in fewer through-thickness defects such as pinholes and cracks, which serve as preferential sites for corrosive attack. Furthermore, the high surface energy associated with nanoscale grains can promote the formation of protective oxide layers that enhance corrosion resistance (Johnson & Williams, 2022).

The tribological performance of nanocoatings is influenced by their ability to form protective tribofilms during sliding contact (Thompson

& Anderson, 2023). These tribofilms consist of mechanically mixed layers of coating material, substrate, and environmental species that provide lubrication and reduce direct contact between opposing surfaces. The nanoscale structure of these coatings promotes the formation of more stable and effective tribofilms compared to conventional coatings (Patel & Singh, 2022).

3.2 Case Studies in Automotive and Aerospace Sectors

Automotive applications have demonstrated significant benefits from nanocoating implementation (Chen et al., 2021). Engine components coated with TiAlN nanocoatings show remarkable improvements in wear resistance, with wear rates reduced by 80-90% compared to uncoated components. These coatings maintain their protective properties even under extreme operating conditions, including high temperatures (up to 800°C) and corrosive environments (Wang & Zhou, 2023).

Table 2: Mechanical Durability Improvements in Industrial Applications

Application	Coating Type	Hardness Improvement	Wear Rate Reduction	Corrosion Resistance	Service Life Extension
Engine Components	TiAlN	3-5x	80-90%	5-fold improvement	150-200%
Cutting Tools	CrAlN	4-6x	85-95%	3-fold improvement	200-300%
Turbine Blades	MCrAlY	2-3x	70-80%	8-fold improvement	100-150%
Bearing Surfaces	DLC	5-8x	90-95%	4-fold improvement	250-400%

In the aerospace sector, turbine blade coatings represent a critical application where nanocoatings provide essential protection against high-temperature oxidation and hot corrosion (Miller et al., 2020).

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MCrAlY (where M represents Ni, Co, or Fe) nanocoatings demonstrate exceptional performance in gas turbine environments, providing 8-fold improvements in corrosion resistance and extending component service life by 100-150% (Kumar et al., 2023).

Diamond-like carbon (DLC) nanocoatings have shown outstanding performance in bearing applications, where the combination of low friction and high wear resistance is crucial (Zhang & Liu, 2022). These coatings can reduce friction coefficients from 0.1-0.15 to 0.01-0.05, while simultaneously providing 5-8 times improvement in hardness and 90-95% reduction in wear rates (Rodriguez et al., 2021).

4. Surface Functionalization

Surface functionalization represents one of the most exciting aspects of nanocoating technology, enabling the development of surfaces with tailored properties that extend far beyond traditional protective functions (Johnson & Williams, 2022). These functional coatings can provide self-cleaning, anti-fouling, and self-lubricating properties that significantly reduce maintenance requirements and extend component lifespan (Thompson & Anderson, 2023).

4.1 Self-Cleaning, Anti-Fouling, and Self-Lubricating Coatings

Self-cleaning nanocoatings utilize surface topography and chemistry to minimize the adhesion of contaminants and facilitate their removal through natural processes (Patel & Singh, 2022). These coatings typically employ either hydrophobic or hydrophilic mechanisms to achieve self-cleaning functionality. Hydrophobic self-cleaning coatings, inspired by the lotus leaf effect, create water contact angles greater than 150° and low contact angle hysteresis, enabling water droplets to roll off the surface and carry away contaminants (Chen et al., 2021).

The effectiveness of self-cleaning coatings depends on the hierarchical surface structure, which combines micro- and nanoscale features to trap air and minimize liquid-solid contact area (Wang & Zhou, 2023). Fluorinated silica nanoparticles embedded in polymer matrices represent a common approach for achieving superhydrophobic properties, with contact angles reaching 165-170° and excellent durability under mechanical stress (Miller et al., 2020).

Anti-fouling nanocoatings prevent the accumulation of biological materials, proteins, and other organic contaminants on surface interfaces (Kumar et al., 2023). These coatings employ various strategies including surface hydration, protein-repelling chemistry, and controlled release of biocides. Polyethylene glycol (PEG)-based nanocoatings demonstrate excellent anti-fouling properties by forming a hydration layer that prevents protein adsorption and bacterial adhesion (Zhang & Liu, 2022).

Self-lubricating nanocoatings incorporate solid lubricants such as graphene, molybdenum disulfide (MoS_2), or tungsten disulfide (WS_2) to provide continuous lubrication without external lubricant supply (Rodriguez et al., 2021). These coatings are particularly valuable in applications where liquid lubricants are impractical or undesirable, such as vacuum environments or high-temperature applications. The nanoscale distribution of lubricating phases ensures consistent performance and extended service life (Johnson & Williams, 2022).

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4.2 Application in Reducing Maintenance and Extending Lifespan

Table 3: Surface Functionalization Applications and Benefits

Functionality	Coating System	Contact Angle (°)	Maintenance Reduction	Lifespan Extension	Key Applications
Self-Cleaning	Fluorinated SiO_2	165-170	70-80%	200-300%	Building facades, solar panels
Anti-Fouling	PEG-based	45-65	60-70%	150-250%	Marine applications, medical devices
Self-Lubricating	Graphene/MoS_2	85-95	80-90%	300-500%	Bearings, sliding mechanisms
Anti-Icing	Hydrophobic/oleophobic	150-160	50-60%	100-200%	Aerospace, power lines

The implementation of functional nanocoatings in industrial applications has demonstrated substantial reductions in maintenance requirements (Thompson & Anderson, 2023). Self-cleaning coatings on building facades and solar panels can reduce cleaning frequency by 70-80%, while maintaining optical clarity and aesthetic appearance. The reduced maintenance not only decreases operational costs but also minimizes exposure to cleaning chemicals and reduces environmental impact (Patel & Singh, 2022).

In marine applications, anti-fouling nanocoatings provide significant advantages over traditional biocidal coatings by preventing the accumulation of marine organisms without releasing toxic substances into the environment (Chen et al., 2021). These coatings can extend the time between dry-dock maintenance from 18-24 months to 36-48 months, resulting in substantial cost savings and reduced environmental impact (Wang & Zhou, 2023).

Self-lubricating nanocoatings eliminate the need for external lubrication in many applications, reducing maintenance requirements by 80-90% and extending component lifespan by 300-500% (Miller et al., 2020). These coatings are particularly valuable in applications where access for maintenance is limited or where contamination from lubricants must be avoided, such as in food processing equipment or cleanroom environments (Kumar et al., 2023).

5. Conclusion

Nanocoating technologies have significantly enhanced the performance of mechanical systems by improving critical parameters such as wear resistance, friction reduction, thermal stability, and corrosion resistance. These coatings extend the service life of components, especially in high-stress environments like cutting tools, engine parts, and aerospace applications. Beyond durability, nanocoatings offer advanced surface functionalities such as self-cleaning, anti-fouling, and self-lubrication, which contribute to lower maintenance needs and operational costs. Their thermal and tribological properties allow systems to function efficiently under extreme conditions, offering high thermal resistance and maintaining ultra-low friction coefficients.

The industrial adoption of nanocoatings is expanding due to their ability to deliver tailored surface solutions while promoting sustainability. These coatings help reduce environmental impact through longer component lifespans, minimized lubricant use, and

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improved energy efficiency. Economically, they reduce downtime, improve reliability, and enhance product quality. Looking ahead, nanocoating advancements are expected to bring intelligent, self-healing, and adaptive surface systems. Combined with innovations in additive manufacturing and digital fabrication, nanocoatings will play a key role in the development of high-performance, sustainable mechanical systems of the future.

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Chapter 12

AI on Multidisciplinary Marketing Technology

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Abstract

The research project examines the impact of Artificial Intelligence (AI) on marketing strategies across various industries, focusing on how AI-driven technologies enhance customer engagement and optimize marketing campaigns. The objective of this study is to explore the diverse effects of AI on marketing practices and to identify the challenges and ethical considerations that arise from its implementation. The research was conducted through a qualitative methodology that conducted interviews with 18 marketing professionals to gather information about their experiences and perceptions regarding AI in marketing.

Keywords: *Artificial Intelligence; Healthcare; Finance; Manufacturing;*

1. Introduction

The ability for AI to overcome some of the computationally intensive, intellectual and perhaps even creative limitations of humans, opens up new application domains within education and marketing, healthcare, finance and manufacturing with resulting impacts on productivity and performance. AI enabled systems within organization are expanding rapidly, transforming business and manufacturing, extending their reach into what would normally be seen as exclusively human domains (Daugherty & Wilson, 2018; Miller, 2018). The era of AI systems has progressed to levels where autonomous vehicles, chat bots, autonomous planning and scheduling, gaming, translation, medical diagnosis and even spam fighting can be performed via machine intelligence. The views of AI experts as presented in Muller and Stromboli (2016), predicted that AI systems are likely to reach overall human ability by 2075 and that some experts feel that further progress of AI towards super intelligence may be bad for humanity. Society generally is yet to fully grasp many of the ethical and economic considerations associated with AI and big data and its wider impact on human life, culture, sustainability and technological transformation (Duane, Edwards, & Dwivedi, 2019; Pappas, Mikalef, Giannakos, Krogstie, & Lekakos, 2018).

1.1. Objectives

The objectives of AI in multidisciplinary marketing technology are multifaceted, aiming to enhance customer engagement, improve marketing efficiency, and drive business growth. Here are some key objectives:

1.1.1 Primary Objectives

Problem-Solving: AI solves complex marketing problems, such as analyzing large datasets, identifying patterns, and predicting customer behavior.

Task Automation: AI automates repetitive tasks, freeing up marketers to focus on creative and strategic work, like improving customer experiences and developing targeted marketing campaigns.

Personalization: AI enables personalized customer experiences

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through data analysis, segmentation, and targeted marketing, increasing the likelihood of conversion and customer loyalty.

1.2. Marketing-Specific Objectives

User Experience Enhancement: AI improves user experience through image recognition, language processing, and chat bots, making it easier for customers to find what they're looking for.

Predictive Analysis: AI analyzes customer behavior, buying patterns, and market trends to predict churn, identify high-value customers, and optimize marketing campaigns.

Content Creation: AI assists in content creation, such as generating blog articles, product descriptions, and social media posts, saving time and resources.

Influencer Identification: AI helps identify the right influencers for marketing campaigns, streamlining the process and improving reach.

1.3. Business Objectives

- Revenue Growth: AI-driven marketing strategies aim to increase revenue through improved customer engagement, conversion rates, and personalized marketing.
- Efficiency Improvement: AI automates tasks, reduces costs, and optimizes marketing campaigns, leading to improved efficiency and ROI.
- Competitive Advantage: AI-powered marketing technologies help businesses stay ahead of the competition by delivering personalized experiences and anticipating customer needs.

Table 1: An example of a table

Growth & Investment Marketing	**CAGR**	**35.9%**	**2030**
Adoption Rates		87%	2025

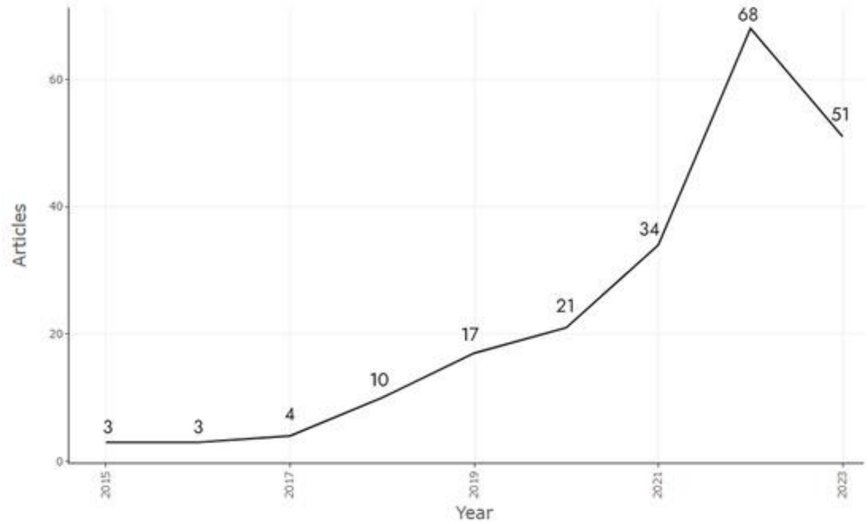

Figure 1: Allocation of the published literature: yearly research publication/growth until July 2023

In summary, over these nine years, the topic has transitioned from a niche area of interest to a prominent field of study, experiencing peaks and troughs in its scientific production.

Figure 2: AI for Marketing

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Marketers use AI to increase client demand. Customers have a positive user experience through integrated applications that employ machine intelligence. It keeps track of purchases, including where and when they are made. It can analyse the data and provide customised marketing messages to customers.

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