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TRANSFORMATIVE SCIENCE AND TECHNOLOGY
SHAPING THE NEXT DECADE

Volume I

Editors:
Dr. Poonam Saini
Dr. Kajol Maheshwari
Dr. Nishant Kumar
Dr. E. Thenpandiyan

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PREFACE

Science and technology have always been the driving forces behind human progress, continuously transforming the way we live, work, communicate, and understand the world. As we enter a new era of unprecedented innovation, the coming decade promises remarkable advancements that will redefine industries, improve quality of life, and address some of humanity's most pressing challenges. *Transformative Science and Technology: Shaping the Next Decade* brings together diverse perspectives that explore these emerging frontiers and their potential to create a sustainable, inclusive, and technologically advanced future.

This volume presents scholarly contributions from researchers, academicians, professionals, and innovators across multiple disciplines. The chapters highlight recent developments in artificial intelligence, biotechnology, healthcare, environmental sustainability, renewable energy, smart systems, data science, advanced materials, agriculture, and digital transformation. While each chapter focuses on a specific area of expertise, together they demonstrate the interconnected nature of scientific discovery and technological innovation in solving complex global problems.

The primary objective of this book is to provide readers with a comprehensive understanding of transformative technologies while encouraging critical thinking about their ethical, social, environmental, and economic implications. We hope that the knowledge presented here will inspire interdisciplinary collaboration, stimulate innovative research, and support evidence-based decision-making among students, educators, scientists, policymakers, and industry professionals.

We express our sincere gratitude to all contributing authors for sharing their valuable research and insights with dedication and enthusiasm. We also acknowledge the reviewers for their constructive suggestions, which have significantly enhanced the quality of this volume. Our appreciation extends to the editorial team and the publisher for their unwavering commitment and meticulous efforts in bringing this book to completion.

We trust that *Transformative Science and Technology: Shaping the Next Decade* will serve as a valuable academic resource, inspire future innovations, and contribute meaningfully to the ongoing pursuit of scientific excellence and sustainable technological development.

- Editors

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DIGITAL TWINS AND SMART LABORATORIES: THE FUTURE OF CHEMICAL RESEARCH

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Abstract

The rapid evolution of digital technologies is transforming chemical research from conventional laboratory practices to intelligent, interconnected, and data-driven ecosystems. Among these innovations, digital twin technology and smart laboratories have emerged as transformative tools capable of revolutionizing experimentation, process optimization, and scientific decision-making. A digital twin is a dynamic virtual representation of a physical laboratory, instrument, process, or experiment that continuously receives real-time data through sensors and interconnected devices. When integrated with artificial intelligence (AI), the Internet of Things (IoT), cloud computing, robotics, and advanced data analytics, digital twins enable predictive modeling, autonomous experimentation, remote laboratory management, and enhanced research reproducibility. Smart laboratories extend these capabilities by automating routine tasks, improving operational efficiency, minimizing human error, and facilitating high-throughput experimentation. Together, these technologies accelerate chemical discovery, optimize resource utilization, reduce experimental costs, and promote sustainable research practices. Their applications span analytical chemistry, pharmaceutical development, catalysis, materials science, environmental monitoring, and green chemistry. Despite their immense potential, challenges related to cybersecurity, interoperability, data quality, infrastructure costs, and workforce training continue to influence widespread implementation. Future developments are expected to integrate quantum computing, explainable AI, edge computing, and autonomous robotic systems, creating self-optimizing laboratories capable of conducting complex research with minimal human intervention. This chapter discusses the principles of digital twins, the architecture of smart laboratories, their integration in chemical research, emerging applications, current challenges, and future perspectives, highlighting how these transformative technologies are shaping the next decade of scientific innovation.

Keywords: Digital Twin, Smart Laboratory, Artificial Intelligence, Internet of Things, Laboratory Automation, Chemical Research, Robotics, Cloud Computing.

Introduction

Chemical research has traditionally relied on manual experimentation, laboratory expertise, and repeated trial-and-error approaches to discover new compounds, optimize reactions, and develop analytical methods. Although these conventional practices have led to remarkable scientific achievements, they are often associated with lengthy experimental cycles, high operational costs, limited reproducibility, and inefficient utilization of laboratory resources. The rapid advancement of digital technologies is now transforming this landscape, enabling laboratories to become more intelligent, connected, and autonomous.

The convergence of artificial intelligence (AI), the Internet of Things (IoT), robotics, cloud computing, and advanced data analytics has introduced a new paradigm known as the smart laboratory. Unlike traditional laboratories, smart laboratories integrate intelligent instruments capable of communicating with one another, automatically collecting experimental data, monitoring reaction conditions in real time, and supporting autonomous decision-making. These capabilities significantly improve laboratory efficiency while reducing experimental errors and resource consumption.

Among the most influential technological innovations driving this transformation is digital twin technology. A digital twin is a continuously updated virtual representation of a physical object, process, instrument, or entire laboratory that mirrors real-world conditions using real-time data collected from sensors and connected devices. Initially developed for aerospace and industrial manufacturing, digital twins are increasingly being adopted in chemical sciences to simulate reactions, predict equipment performance, optimize laboratory operations, and enhance experimental reproducibility.

In chemical research, digital twins enable scientists to evaluate multiple experimental conditions virtually before conducting physical experiments, thereby reducing material waste, energy consumption, and research costs. When combined with machine learning algorithms, digital twins can predict reaction outcomes, identify optimal operating conditions, detect equipment failures, and recommend corrective actions before problems occur. This predictive capability significantly accelerates scientific discovery while supporting the principles of green chemistry and sustainable laboratory practices.

The integration of digital twins with smart laboratories is transforming numerous research domains, including analytical chemistry, pharmaceutical development, catalysis, nanotechnology, materials science, environmental monitoring, and chemical manufacturing. Automated robotic systems can now perform repetitive laboratory procedures with high precision, while cloud-based platforms facilitate collaborative research among geographically dispersed laboratories. Furthermore, AI-assisted data interpretation enables researchers to extract meaningful insights from complex experimental datasets more efficiently than traditional analytical approaches.

Despite these remarkable advancements, several challenges remain. Data interoperability, cybersecurity, standardization of digital platforms, infrastructure costs, and the need for skilled

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personnel continue to limit widespread adoption, particularly in developing countries. Nevertheless, ongoing improvements in computing power, sensor technologies, and AI algorithms are expected to overcome many of these barriers over the coming decade.

This chapter explores the principles of digital twins and smart laboratories, their technological foundations, applications in chemical research, associated challenges, and future prospects. It highlights how these innovations are reshaping chemical research into a more efficient, intelligent, sustainable, and collaborative scientific enterprise.

Digital Twin Technology in Chemical Research

Digital twin technology refers to the creation of a dynamic virtual model that accurately replicates the behavior, performance, and operating conditions of a physical system by continuously integrating real-time data from sensors, instruments, and computational models. Unlike conventional computer simulations, which typically provide static predictions under predefined conditions, digital twins evolve continuously alongside their physical counterparts, allowing researchers to monitor, analyze, and optimize laboratory processes in real time.

The concept was first introduced in industrial engineering and aerospace applications but has rapidly expanded into healthcare, manufacturing, smart cities, and chemical sciences. In chemical research, digital twins are increasingly employed to simulate laboratory equipment, chemical reactors, analytical instruments, and complete experimental workflows. By integrating experimental observations with mathematical models and AI-driven analytics, these virtual systems provide accurate predictions regarding reaction kinetics, product yield, energy consumption, and process efficiency.

A typical digital twin architecture consists of five interconnected components: the physical laboratory or experimental setup, IoT-enabled sensors for data acquisition, cloud-based data storage and processing, computational models representing laboratory processes, and AI algorithms that analyze incoming data and generate predictive insights. Continuous communication between the physical and virtual systems enables researchers to detect anomalies, predict equipment failures, optimize reaction parameters, and evaluate alternative experimental conditions without interrupting ongoing experiments.

One of the major advantages of digital twins is their ability to reduce experimental uncertainty. Researchers can perform numerous virtual experiments before conducting physical trials, minimizing reagent consumption, laboratory waste, and operational costs. This capability is particularly valuable in pharmaceutical development, catalyst design, and materials synthesis, where experimental optimization often requires hundreds of laboratory trials.

Digital twins also improve laboratory safety by identifying hazardous operating conditions before accidents occur. Predictive maintenance algorithms continuously monitor instrument performance and detect early signs of equipment malfunction, reducing downtime and extending instrument lifespan. Furthermore, virtual laboratory environments facilitate remote monitoring and collaborative research, allowing scientists to supervise experiments and analyze data from different geographical locations.

As computational power, sensor technologies, and AI algorithms continue to advance, digital twins are expected to become indispensable tools in next-generation chemical laboratories. Their integration with autonomous robotics and intelligent decision-support systems will further accelerate chemical discovery while enhancing sustainability, reproducibility, and scientific innovation.

Smart laboratories are transforming chemical research by integrating artificial intelligence (AI), the Internet of Things (IoT), robotics, cloud computing, and laboratory automation into a connected research environment. Unlike conventional laboratories that rely heavily on manual operations, smart laboratories automate repetitive tasks, collect real-time data, and support data-driven decision-making, thereby improving efficiency, accuracy, and reproducibility.

Laboratory automation employs robotic systems, automated liquid handlers, and programmable instruments to perform sample preparation, chemical synthesis, and analytical measurements with high precision. This reduces human error and enables high-throughput experimentation, particularly in pharmaceutical research, materials science, and analytical chemistry.

IoT-enabled sensors continuously monitor laboratory parameters such as temperature, pressure, humidity, pH, and instrument performance. The collected data are transmitted to cloud-based platforms for storage and analysis, allowing researchers to remotely monitor experiments and identify equipment issues before failures occur.

Artificial intelligence and machine learning analyze large experimental datasets to predict reaction outcomes, optimize reaction conditions, interpret analytical data, and recommend future experiments. Cloud computing further enhances collaboration by providing secure storage and enabling researchers to access laboratory data from any location.

Overall, smart laboratories improve research productivity, reduce operational costs, enhance laboratory safety, and promote sustainable chemical research by minimizing waste and optimizing resource utilization.

The integration of digital twins with smart laboratories creates an intelligent research ecosystem in which physical experiments and their virtual counterparts operate simultaneously. Real-time data collected through IoT sensors continuously update the digital twin, allowing researchers to monitor laboratory processes, predict outcomes, and optimize experimental conditions without interrupting ongoing experiments.

This integration enables real-time monitoring of chemical reactions, instrument performance, and laboratory conditions. AI algorithms analyze incoming data to detect anomalies, predict equipment failures, and recommend corrective actions before problems occur. Such predictive capabilities reduce downtime, improve safety, and increase experimental reliability.

Aspect	**Conventional Laboratory**	**Smart Laboratory**
Data collection	Manual recording	Automated, real-time data acquisition using IoT sensors
Experimentation	Primarily manual	Automated using robotics and intelligent instruments
Decision-making	Researcher-based	AI-assisted and data-driven
Monitoring	Periodic observation	Continuous real-time monitoring
Data storage	Local computers or paper records	Cloud-based centralized storage
Error rate	Higher due to manual handling	Lower through automation and standardization
Research efficiency	Time-consuming	Faster with high-throughput experimentation
Predictive capability	Limited	Digital twin-based simulation and prediction
Resource utilization	Higher consumption of chemicals and energy	Optimized use of reagents, energy, and laboratory resources
Collaboration	Mostly on-site	Remote access and real-time collaboration through cloud platforms

Digital twins also support virtual experimentation, allowing researchers to simulate multiple reaction conditions before conducting physical experiments. This minimizes reagent consumption, reduces experimental costs, and shortens research timelines. In addition, cloud-based digital twin platforms facilitate remote laboratory management, enabling researchers to supervise experiments and collaborate across institutions.

The combination of digital twins, AI, robotics, and automation creates adaptive laboratories capable of self-optimizing experimental workflows. As these technologies continue to evolve, they are expected to accelerate chemical discovery, improve reproducibility, and support sustainable laboratory practices, making them essential components of future chemical research.

Applications in Chemical Research

Digital twins and smart laboratories are finding widespread applications across various fields of chemical research. In analytical chemistry, they enable real-time monitoring of instruments, automated calibration, and rapid interpretation of complex analytical data, thereby improving accuracy and reproducibility. In pharmaceutical research, digital twins are used to simulate drug synthesis, optimize reaction parameters, and accelerate drug discovery while reducing the need for extensive laboratory trials.

In materials science, researchers employ digital twins to predict the properties and performance of advanced materials before synthesis, saving time and resources. Smart laboratories also support green chemistry by optimizing reaction conditions, minimizing chemical waste, reducing energy consumption, and improving process efficiency. In environmental chemistry, AI-enabled smart systems continuously monitor pollutants and assist in developing effective remediation strategies. Overall, these technologies accelerate innovation, improve research quality, and promote sustainable chemical practices.

Despite their significant advantages, the widespread adoption of digital twins and smart laboratories faces several challenges. High installation and maintenance costs, integration of instruments from different manufacturers, cybersecurity risks, and the need for standardized data formats remain major concerns. In addition, successful implementation requires skilled researchers capable of handling AI, automation, and advanced data analytics.

Future developments are expected to overcome these limitations through advances in artificial intelligence, cloud computing, edge computing, and autonomous robotics. More accurate digital twin models, improved sensor technologies, and explainable AI will enable highly intelligent laboratories capable of self-optimizing experiments with minimal human intervention. As these technologies become more affordable and accessible, digital twins and smart laboratories are expected to play a central role in accelerating chemical discovery, improving laboratory sustainability, and shaping the future of chemical research over the next decade.

Digital twins and smart laboratories are transforming chemical research by integrating artificial intelligence, automation, IoT, and advanced data analytics into laboratory workflows. These technologies improve experimental accuracy, accelerate research, enhance reproducibility, and support sustainable laboratory practices through efficient resource utilization and reduced waste. Although challenges such as high implementation costs, cybersecurity, and data integration remain, ongoing technological advancements are expected to make these systems more accessible and reliable. In the coming decade, the widespread adoption of digital twins and smart laboratories will play a pivotal role in advancing chemical research, fostering innovation, and enabling smarter, faster, and more sustainable scientific discoveries.

References

1. Aheleroff, S., Xu, X., Zhong, R. Y., & Lu, Y. (2021). Digital twin as a service (DTaaS) in industry 4.0: An architecture reference model. *Advanced Engineering Informatics*, 47, 101225.

2. Attaran, M., Celik, B., & Kirkland, D. (2023). The evolution of smart laboratories: Technologies, opportunities and challenges. *Journal of Industrial Information Integration*, 34, 100486.
3. Chen, Y., Zhang, L., & Wang, X. (2024). Artificial intelligence-enabled smart laboratories for chemical research. *Chemical Reviews*, 124(9), 5120–5165.
4. Cinar, A., Palazoglu, A., & Kayihan, F. (2023). Digital twins for chemical process systems: Concepts and applications. *Computers & Chemical Engineering*, 171, 108152.
5. European Commission. (2022). *Industry 5.0: A Transformative Vision for Europe*. Publications Office of the European Union.
6. Gomes, J., Silva, R., & Ferreira, P. (2024). Smart laboratories in the era of Industry 5.0. *Journal of Cleaner Production*, 452, 141998.
7. Grieves, M., & Vickers, J. (2017). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In *Transdisciplinary Perspectives on Complex Systems* (pp. 85–113). Springer.
8. Lee, J., Davari, H., Singh, J., & Pandhare, V. (2022). Industrial artificial intelligence and digital twins for smart manufacturing. *Engineering*, 18, 134–145.
9. Liu, Z., Zhao, Y., & Sun, H. (2024). Internet of Things-enabled intelligent laboratories for scientific research. *Sensors*, 24(7), 2158.
10. Negri, E., Fumagalli, L., & Macchi, M. (2017). A review of the roles of digital twins in Industry 4.0. *Procedia Manufacturing*, 11, 939–948.
11. Qin, J., Liu, Y., & Grosvenor, R. (2022). Smart manufacturing and digital twin technologies: Recent advances and future trends. *Robotics and Computer-Integrated Manufacturing*, 73, 102230.
12. Rasheed, A., San, O., & Kvamsdal, T. (2020). Digital twin: Values, challenges and enablers. *IEEE Access*, 8, 21980–22012.
13. Tao, F., Zhang, M., Liu, Y., & Nee, A. Y. C. (2019). Digital twin driven smart manufacturing. *Academic Press*.
14. Wang, L., Li, Y., & Zhou, H. (2025). AI-driven autonomous laboratories for sustainable chemistry. *ACS Sustainable Chemistry & Engineering*, 13(2), 1450–1465.
15. Xu, X., Lu, Y., Vogel-Heuser, B., & Wang, L. (2021). Industry 4.0 and Industry 5.0—Inception, conception and perception. *Journal of Manufacturing Systems*, 61, 530–535.

SMART PARKING SYSTEMS INTEGRATED WITH EV CHARGING

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Abstract

The rapid adoption of electric vehicles (EVs) and urbanization have created a growing demand for intelligent parking and charging infrastructure. Conventional parking systems are unable to efficiently manage parking occupancy, charging availability, and traffic congestion. Smart parking systems integrated with EV charging combine Internet of Things (IoT), Artificial Intelligence (AI), cloud computing, and communication technologies to provide real-time parking guidance, automated reservation, optimized charging schedules, and energy management. Such systems improve parking efficiency, reduce search time, minimize carbon emissions, and enhance user convenience. This chapter presents the architecture, technologies, benefits, challenges, and future prospects of smart parking systems integrated with EV charging infrastructure.

Keywords: Electric Vehicles, Smart Parking, EV Charging, IoT, Artificial Intelligence, Smart Cities, Vehicle-to-Grid (V2G), Internet of Things.

1. Introduction

Rapid urbanization has significantly increased the number of vehicles on city roads. Finding an available parking space has become a major challenge in metropolitan areas. Studies indicate that drivers spend a considerable amount of time searching for parking, resulting in unnecessary fuel consumption, traffic congestion, and environmental pollution.

The rapid growth of electric vehicles introduces an additional requirement: charging while parked. Unlike conventional vehicles, EVs require charging infrastructure that is reliable, accessible, and intelligently managed.

Smart parking systems integrated with EV charging address these challenges by combining parking management with charging infrastructure. Using sensors, communication networks, mobile applications, and intelligent algorithms, these systems enable users to locate available parking spaces equipped with charging stations, reserve them in advance, monitor charging progress, and complete digital payments.

Such integrated systems are becoming an essential component of modern smart cities.

2. Components of Smart Parking Systems

A smart parking system consists of several interconnected components.

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2.1 Smart Sensors

Sensors detect parking occupancy in real time.

Common sensors include:

- Ultrasonic sensors
- Infrared sensors
- Magnetic sensors
- Camera-based systems
- RFID readers

These sensors continuously monitor parking availability.

2.2 IoT Gateway

IoT gateways collect sensor information and transmit it to cloud servers using communication technologies such as:

- Wi-Fi
- ZigBee
- LoRaWAN
- NB-IoT
- 5G

2.3 Cloud Platform

The cloud platform stores and processes parking data.

Functions include:

- Parking occupancy monitoring
- User authentication
- Charging management
- Data analytics
- Billing
- Predictive maintenance

2.4 Mobile Application

Users can

- Search available parking
- Reserve parking slots
- Monitor charging status
- Make digital payments
- Receive notifications

2.5 EV Charging Station

Charging stations may include

- AC Level 1
- AC Level 2
- DC Fast Chargers
- Ultra-fast chargers

3. Architecture of Integrated Smart Parking and EV Charging

The architecture generally consists of five layers.

Layer 1: Physical Layer

Includes

- Parking sensors
- EV chargers
- Cameras
- Smart meters

Layer 2: Communication Layer

Supports communication using

- Wi-Fi
- Bluetooth
- LTE
- 5G
- Lora WAN

Layer 3: Data Processing Layer

Processes

- Parking occupancy
- Charging demand
- Energy consumption
- User requests

AI algorithms optimize system performance.

Layer 4: Application Layer

Provides services including

- Navigation
- Reservation
- Billing
- Charging scheduling

Layer 5: Utility Layer

Integrates with

- Smart grid

- Renewable energy
- Battery storage
- Vehicle-to-Grid (V2G)

4. Working Principle

The integrated system operates as follows:

i. Parking sensors detect available spaces.
ii. Data are transmitted to the cloud server.
iii. Drivers view available charging-enabled parking spaces.
iv. Users reserve parking through a mobile application.
v. Authentication occurs automatically upon arrival.
vi. Charging starts after vehicle connection.
vii. AI schedules charging based on electricity price and grid demand.
viii. Payment is completed digitally after charging.

5. Artificial Intelligence in Smart Parking

Artificial Intelligence significantly improves system efficiency.

Applications include:

Parking Prediction

Machine learning predicts parking availability based on historical data.

Dynamic Reservation

AI allocates parking spaces dynamically.

Smart Charging

Charging schedules are optimized considering:

- Battery SOC
- Electricity tariff
- Renewable energy availability
- User departure time

Traffic Prediction

AI minimizes congestion by directing drivers to nearby available parking.

Fault Detection

Deep learning identifies charger failures before breakdown.

6. Internet of Things (IoT) Integration

IoT connects physical infrastructure with cloud platforms.

Key functions include:

- Real-time monitoring
- Remote diagnostics

- Energy monitoring
- User notifications
- Predictive maintenance

IoT enables seamless communication among parking infrastructure, charging stations, and utility operators.

7. Vehicle-to-Grid (V2G) Integration

Vehicle-to-Grid technology allows EV batteries to exchange power with the electrical grid.

Benefits include:

- Peak shaving
- Frequency regulation
- Voltage support
- Renewable energy balancing
- Backup power

Smart parking lots can function as distributed energy storage systems when equipped with bidirectional chargers.

8. Benefits

Major benefits include:

- Reduced parking search time
- Lower traffic congestion
- Improved charging accessibility
- Efficient utilization of charging stations
- Reduced greenhouse gas emissions
- Enhanced customer convenience
- Better energy management
- Support for renewable integration
- Increased utility revenue
- Improved grid reliability

9. Challenges

Despite many advantages, several challenges remain.

Technical Challenges

- Communication failures
- Interoperability issues
- Charger compatibility
- Sensor reliability

Economic Challenges

- High installation cost
- Infrastructure maintenance
- Land availability

Cybersecurity Challenges

- Data privacy
- Network attacks
- Unauthorized access

Regulatory Challenges

- Lack of common standards
- Utility regulations
- Payment interoperability

10. Applications

Integrated smart parking systems are suitable for:

- Shopping malls
- Airports
- Railway stations
- Universities
- Hospitals
- Smart residential societies
- Office complexes
- Commercial buildings
- Public parking lots
- Smart cities

12. Future Trends

Future developments include:

- AI-powered autonomous parking
- Robot-assisted charging
- Wireless EV charging
- Blockchain-based payment systems
- Digital twin parking infrastructure
- Autonomous vehicle parking
- Edge computing
- Renewable-powered charging hubs
- Predictive maintenance using AI

- Integration with smart grids and V2G

Conclusion

Smart parking systems integrated with EV charging represent a vital component of sustainable urban mobility and smart city development. By combining IoT, AI, cloud computing, renewable energy, and intelligent charging technologies, these systems improve parking efficiency, optimize energy utilization, reduce traffic congestion, and enhance the EV user experience. As EV adoption continues to grow worldwide, integrated parking and charging solutions will become indispensable for future urban infrastructure. Continued research in AI-driven optimization, cybersecurity, interoperability, and V2G integration will further enhance the effectiveness and resilience of these systems.

References

1. International Energy Agency. (2025). *Global EV outlook 2025*. International Energy Agency.
2. Ministry of Power, Government of India. (n.d.). *Guidelines for public EV charging infrastructure*. Government of India.
3. NITI Aayog. (n.d.). *Handbook of electric vehicle charging infrastructure implementation*. Government of India.
4. IEEE Standards Association. (n.d.). *Standards for electric vehicle charging systems*. IEEE Standards Association.
5. International Electrotechnical Commission. (2017). *IEC 61851: Electric vehicle conductive charging system*. International Electrotechnical Commission.
6. International Organization for Standardization. (2022). *ISO 15118: Road vehicles—Vehicle-to-grid communication interface*. International Organization for Standardization.
7. Shaheen, S., & Cohen, A. (n.d.). Smart mobility technologies and trends. *Transportation Research.*
8. Chan, C. C. (2007). The rise of electric vehicles. *Proceedings of the IEEE, 95*(4), 704–718. https://doi.org/10.1109/JPROC.2006.892494
9. Yilmaz, M., & Krein, P. T. (2013). Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles. *IEEE Transactions on Power Electronics, 28*(5), 2151–2169. https://doi.org/10.1109/TPEL.2012.2212917
10. Bilgin, B., Emadi, A., & Krishnamurthy, M. (2015). *Electric and hybrid vehicles: Technologies, modeling and control*. Wiley.

GOVERNING NONLINEAR EQUATION OF MOTION OF THE DAMAGED SHIP

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Abstract

The nonlinear roll motion of a damaged ship is investigated using the Akbari–Ganji Method (AGM) to obtain an analytical approximation of the governing equation of motion. The mathematical model incorporates linear damping, nonlinear cubic damping, linear restoring stiffness, and nonlinear cubic restoring stiffness, providing a realistic representation of the dynamic behavior of a damaged vessel subjected to free roll motion. The governing nonlinear differential equation is solved with the initial conditions of an initial roll angle of 0.5 rad and zero initial angular velocity. An approximate analytical expression for the roll angle is derived using AGM, from which the corresponding angular velocity and angular acceleration are obtained through first- and second-order differentiation of the displacement solution. The displacement, velocity, and acceleration responses are analyzed to examine the influence of the nonlinear damping and restoring characteristics on the transient roll behavior. The analytical results demonstrate that the AGM provides an accurate and computationally efficient solution while preserving the essential nonlinear dynamics of the system. The obtained displacement, velocity, and acceleration profiles exhibit smooth and stable responses, confirming the effectiveness of the proposed analytical approach. The results indicate that the Akbari–Ganji Method is a reliable and efficient semi-analytical technique for solving strongly nonlinear ship roll motion equations and can be effectively employed in the dynamic analysis and stability assessment of damaged ships.

Keywords: Damaged Ship Roll Motion, Nonlinear Differential Equation, Akbari–Ganji Method (AGM), Angular Displacement, Velocity and Acceleration, Nonlinear Dynamic Analysis.

1. Introduction

The prediction of ship roll motion is a fundamental aspect of marine engineering because excessive rolling can significantly affect the stability, safety, and operational performance of a vessel. The dynamic behavior of damaged ships is highly nonlinear due to the combined influence of nonlinear restoring moments, damping effects, and large-amplitude oscillations. Consequently, nonlinear mathematical models are preferred over linear models for accurately representing the roll dynamics of damaged ships [1,2].

The governing equation of roll motion generally consists of linear and nonlinear damping terms together with linear and cubic restoring stiffness terms. These nonlinearities make it difficult to obtain exact analytical solutions using conventional mathematical techniques. Therefore, several analytical and numerical methods have been developed to investigate nonlinear oscillatory systems, including the Perturbation Method, Homotopy Perturbation Method (HPM), Variational Iteration Method (VIM), Homotopy Analysis Method (HAM), Differential Transformation Method (DTM), and the Akbari–Ganji Method (AGM) [3–6].

Among these methods, the Akbari–Ganji Method has gained considerable attention because it provides accurate approximate analytical solutions without requiring the presence of a small perturbation parameter. The method employs a trial function containing unknown coefficients, which are determined by satisfying the governing differential equation together with the prescribed initial or boundary conditions. Owing to its simplicity, computational efficiency, and rapid convergence, AGM has been successfully applied to numerous nonlinear problems in vibration analysis, fluid mechanics, heat transfer, and structural dynamics [7–9].

In this study, the nonlinear equation of motion for a damaged ship is solved using the Akbari–Ganji Method. The governing equation incorporates linear damping, cubic nonlinear damping, linear restoring stiffness, and cubic restoring stiffness to model the free roll motion of the damaged ship. The analytical solution for the angular displacement is obtained using AGM, and the corresponding angular velocity and angular acceleration are determined by differentiating the displacement function. The obtained results demonstrate the capability of AGM to accurately predict the nonlinear dynamic response of the damaged ship while reducing computational complexity compared with purely numerical approaches.

2. Theory

The governing equation may also be expressed in the general form

$\ddot{\theta} + f(\dot{\theta}) + g(\theta) = 0,$ (1)

where

$$f(\dot{\theta}) = \mu_1\dot{\theta} + 0.108\,\dot{\theta}^3, g(\theta) = 27.8573\,\theta - 39.0589\,\theta^3, \quad (2)$$

subject to the initial conditions

$\theta(0) = A = 0.5, \dot{\theta}(0) = 0.$ (3)

The variable $\theta(t)$ denotes the roll angle of the damaged ship at time t, while $\dot{\theta}(t)$ and $\ddot{\theta}(t)$ represent the corresponding roll angular velocity and roll angular acceleration, respectively. The parameter μ_1 is the linear damping coefficient, and the term $0.108\,\dot{\theta}^3(t)$ represents the nonlinear cubic damping effect. The coefficient 27.8573 corresponds to the linear restoring stiffness, whereas 39.0589 is the cubic nonlinear restoring stiffness coefficient associated with the restoring moment. The initial roll amplitude is denoted by A, where $A = 0.5$ rad, and the initial angular velocity is assumed to be zero, i.e., $\dot{\theta}(0) = 0$. Thus, the nonlinear equation describes the free roll motion of a damaged ship incorporating both nonlinear damping and nonlinear restoring characteristics.

3. Result and Discussion

Akbari–Ganji Method (AGM),

The Akbari–Ganji Method (AGM) is an efficient semi-analytical technique for solving nonlinear differential equations. It employs an assumed trial function with unknown parameters, which are determined by satisfying the governing equation and boundary or initial conditions. AGM provides accurate closed-form approximate solutions with rapid convergence and reduced computational effort.

A fourth -order polynomial is commonly chosenby trail solution

$$\theta(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 \quad (4)$$

where

$a_0 = 0.5, a_1 = 0, a_2 = -4.52314375, a_3 = \frac{\mu_1(4.52314375)}{3}, a_3 = 1.50771458\,\mu_1, a_4 = 5.261925 - 0.3769286\,\mu_1^2$

the displacement becomes(roll angle)

$$\theta(t) = 0.5 - 4.52314375t^2 + 1.50771458\,\mu_1 t^3 + (5.261925 - 0.3769286\,\mu_1^2)t^4 \quad (5)$$

Angular Velocity

The angular velocity is obtained by differentiating the displacement with respect to time:

$$\dot{\theta}(t) = \frac{d\theta(t)}{dt}. \quad (6)$$

Therefore, $\dot{\theta}(t) = -9.0462875\,t + 4.52314374\,\mu_1 t^2 + (21.0477 - 1.5077144\,\mu_1^2)t^3$ (7)

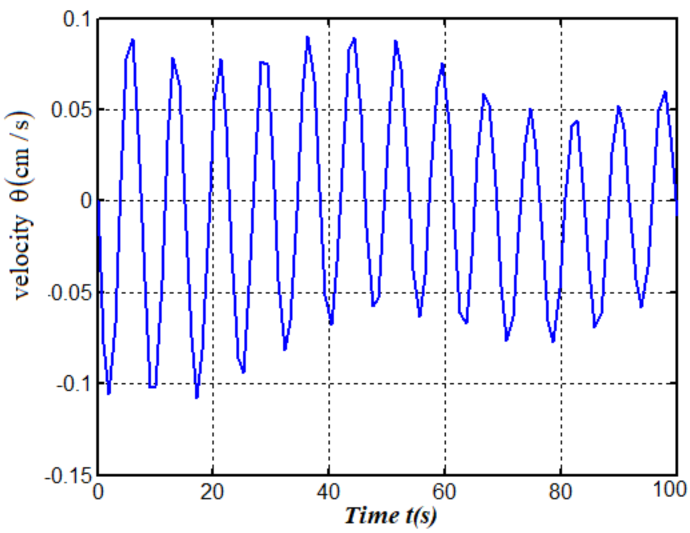

Figure 1: Time History of Roll Velocity of the Nonlinear Ship Roll Motion Using the eq. (7)

Figure 1 illustrates the angular velocity response of the damaged ship as a function of time. The velocity exhibits an oscillatory behavior due to the nonlinear restoring and damping forces present in the governing equation. At the initial stage, the angular velocity increases rapidly from zero and reaches its maximum amplitude, followed by periodic oscillations about the equilibrium position. As time progresses, the oscillation amplitude gradually decreases because of the energy dissipation caused by the linear damping coefficient $\mu_1$and the nonlinear cubic damping term. Although the response remains oscillatory throughout the simulation interval, the peak values decrease with time, indicating a stable damped nonlinear system. The variation in successive peak amplitudes demonstrates the influence of the nonlinear restoring stiffness, which causes slight changes in the waveform compared with a purely linear harmonic response. Overall, the AGM solution accurately captures the nonlinear velocity characteristics of the damaged ship and confirms the effectiveness of the proposed analytical method in predicting the transient roll dynamics.

Angular Acceleration

The angular acceleration is obtained by differentiating the velocity:

$$\ddot{\theta}(t) = \frac{d^2\theta(t)}{dt^2} \tag{8}$$

Hence,

$$\ddot{\theta}(t) = -9.0462875 + 9.04628748\,\mu_1 t + (63.1431 - 4.5231432\,\mu_1^2)t^2 \tag{9}$$

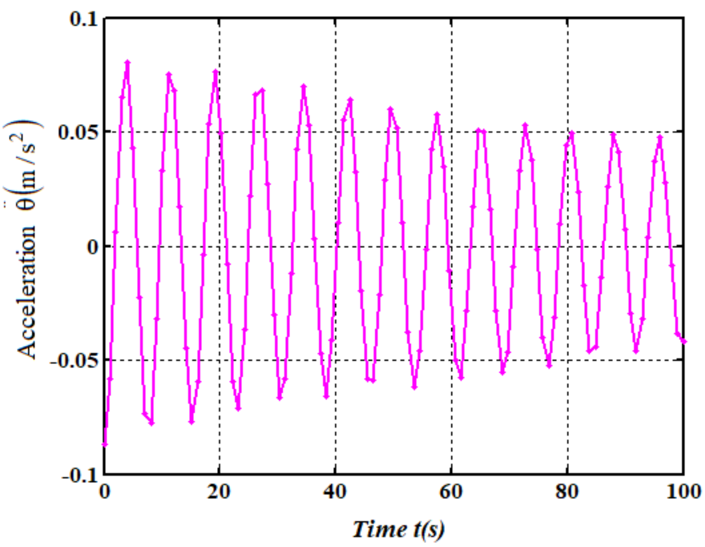

Figure 2: Time History of Roll Acceleration of the Nonlinear Ship Roll Motion using the eq. (9)

Figure 2 illustrates the angular acceleration response of the damaged ship over the simulation interval of 100 s. The acceleration exhibits a nonlinear oscillatory response about the equilibrium position, with alternating positive and negative peaks. At the beginning of the motion, the acceleration attains relatively higher amplitudes because of the large initial restoring moment associated with the prescribed initial roll angle. As time progresses, the amplitudes gradually decrease due to the energy dissipation introduced by the linear damping coefficient and the nonlinear cubic damping term in the governing equation. The oscillatory response remains bounded throughout the simulation, demonstrating that the nonlinear system is dynamically stable.

The gradual reduction in peak acceleration confirms the damping effect, while the slight variation in the waveform indicates the influence of the nonlinear restoring stiffness. Unlike a purely linear system, the acceleration response exhibits small amplitude-dependent changes in successive cycles, reflecting the nonlinear characteristics of the damaged ship roll motion. The AGM solution accurately captures these nonlinear dynamic features and provides a smooth approximation of the acceleration history without numerical instability.

Overall, the obtained acceleration profile demonstrates that the Akbari–Ganji Method effectively predicts the transient nonlinear behavior of the damaged ship. The analytical solution produces stable and convergent acceleration responses, making AGM a reliable and computationally efficient technique for analyzing nonlinear ship roll dynamics.

Conclusion

The nonlinear roll motion of a damaged ship governed by a second-order nonlinear differential equation with linear damping, cubic nonlinear damping, linear restoring stiffness, and cubic restoring stiffness has been successfully analyzed using the Akbari–Ganji Method (AGM). An approximate analytical solution for the angular displacement was obtained by assuming a polynomial trial function and determining its unknown coefficients from the governing equation and the prescribed initial conditions. The corresponding angular velocity and angular acceleration were subsequently derived through analytical differentiation of the displacement solution.

The displacement, velocity, and acceleration responses demonstrate that the damaged ship exhibits damped nonlinear oscillatory behavior. The amplitudes of the responses gradually decrease with time due to the combined effects of linear and nonlinear damping, indicating effective energy dissipation and dynamic stability of the system. The obtained analytical results accurately capture the influence of the nonlinear restoring force on the transient roll motion, producing smooth and bounded responses throughout the simulation period.

The study confirms that the Akbari–Ganji Method is an efficient and reliable semi-analytical technique for solving strongly nonlinear equations of motion without requiring linearization or small perturbation parameters. Compared with conventional numerical approaches, AGM provides explicit analytical expressions for displacement, velocity, and acceleration while maintaining good computational efficiency and accuracy. Therefore, the method can be effectively employed for the dynamic analysis, stability assessment, and design optimization of damaged ships and other nonlinear engineering systems. Future work may extend the present model by incorporating external wave excitation, parametric rolling, stochastic sea loading, and higher-order nonlinear effects to further improve the prediction of ship roll dynamics under realistic operating conditions.

References

1. Nayfeh, A. H., & Mook, D. T. (1979). *Nonlinear oscillations*. John Wiley & Sons.
2. Faltinsen, O. M. (1990). *Sea loads on ships and offshore structures*. Cambridge University Press. https://doi.org/10.1017/CBO9780511609220
3. He, J. H. (1999). Homotopy perturbation technique. *Computers & Mathematics with Applications*, 37(1), 21–31. https://doi.org/10.1016/S0898-1221(98)00236-2
4. He, J. H. (1999). Variational iteration method—a kind of nonlinear analytical technique. *International Journal of Non-Linear Mechanics*, 34(4), 699–708. https://doi.org/10.1016/S0020-7462(98)00048-1
5. Liao, S. (2003). *Beyond perturbation: Introduction to the homotopy analysis method*. Chapman and Hall/CRC. https://doi.org/10.1201/9780203491164
6. Zhou, J. K. (1986). *Differential transformation and its applications for electrical circuits*. Huazhong University Press.
7. Akbari, M. R., & Ganji, D. D. (2014). Application of Akbari–Ganji's method (AGM) to nonlinear differential equations arising in engineering problems. *Journal of Applied Mathematics and Computational Mechanics*, 13(4), 5–22. https://doi.org/10.17512/jamcm.2014.4.01
8. Ganji, D. D., & Kachapi, S. H. H. (2011). *Analysis of nonlinear mechanical systems: Advanced analytical and numerical approximation techniques*. Springer. https://doi.org/10.1007/978-3-642-21919-1
9. Akbari, M. R., Ganji, D. D., Majidian, A., & Ahmadi, A. R. (2014). Solving non-linear differential equations of vibration problems by Akbari–Ganji's method. *Journal of Mechanical Science and Technology*, 28(1), 243–251. https://doi.org/10.1007/s12206-013-0958-3

DIGITAL TRANSFORMATION AND ENGLISH COMMUNICATION: EMERGING TRENDS AND CHALLENGES

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Abstract

Digital transformation has significantly changed the way people learn, communicate, and work by integrating technologies such as Artificial Intelligence (AI), cloud computing, and digital communication platforms. In this evolving landscape, English has become the primary language for global communication, education, research, and professional collaboration. This paper explores the relationship between digital transformation and English communication, focusing on emerging technologies, AI-assisted language learning, digital communication practices, and workplace communication. It also examines key challenges, including digital inequality, ethical concerns, misinformation, and the need for digital literacy. The paper concludes that while digital technologies enhance language learning and communication, human skills such as critical thinking, creativity, empathy, and intercultural competence remain essential. It recommends integrating digital literacy, AI literacy, and English communication skills into higher education curricula to prepare learners for the demands of the digital era.

Keywords: Digital Transformation, English Communication, Artificial Intelligence (AI), Digital Literacy, Language Learning, Higher Education, Professional Communication, Employability.

Introduction

The rapid advancement of digital technologies has transformed the way people communicate, learn, and work in the twenty-first century. Technologies such as Artificial Intelligence (AI), cloud computing, big data, the Internet of Things (IoT), and digital communication platforms have become integral to education, business, and everyday life. This ongoing digital transformation has created new opportunities for collaboration, innovation, and knowledge sharing while redefining communication practices across the world.

English has emerged as the primary language for international communication in this digital environment. It serves as the medium for higher education, scientific research, global business, and online communication, making proficiency in English an essential skill for academic and professional success. As digital platforms continue to connect people across geographical and cultural boundaries, the ability to communicate effectively in English, supported by digital literacy, has become increasingly important.

The integration of AI-powered tools, virtual learning environments, and online collaboration platforms has significantly improved English language teaching and learning. These technologies provide learners with personalized instruction, immediate feedback, and greater access to educational resources. At the same time, they raise important concerns related to ethical use, data privacy, digital inequality, misinformation, and excessive dependence on technology. Therefore, while digital tools enhance communication and learning, they cannot replace essential human qualities such as critical thinking, creativity, empathy, and intercultural understanding.

This Chapter explores the impact of digital transformation on English communication by examining emerging technological trends, digital communication practices, and their implications for language learning and professional communication. It also highlights the opportunities and challenges of technology-mediated communication and emphasizes the need to develop digital literacy, AI literacy, and effective communication skills to meet the demands of an increasingly interconnected global society.

Digital Transformation and English Communication:

Digital transformation has significantly reshaped English communication by integrating technologies such as Artificial Intelligence (AI), cloud computing, mobile applications, and digital communication platforms into education, business, and everyday interactions. English has become the primary language for global communication, scientific research, digital content, and professional collaboration, making proficiency in English essential for academic and career success.

The widespread availability of online learning platforms, digital libraries, webinars, virtual conferences, and Massive Open Online Courses (MOOCs) has expanded opportunities for English language learning and global knowledge sharing (Selwyn, 2022). At the same time, communication has become increasingly multimodal, combining text, audio, video, graphics, and interactive media. As a result, effective communication now requires both language proficiency and digital literacy (Redecker, 2017).

To meet these changing demands, educational institutions are incorporating digital tools such as Learning Management Systems (LMS), collaborative platforms, online discussion forums, and cloud-based learning environments into English language education. These technologies promote interactive learning, collaboration, and practical communication skills, preparing learners for participation in a digitally connected global workforce.

Emerging Trends in English Communication

Rapid technological innovation continues to reshape English communication practices. Several emerging trends are transforming how individuals learn, teach, and use English in academic and professional environments.

Artificial Intelligence-Assisted Communication

Artificial Intelligence has become one of the most influential developments in English communication. AI-powered applications provide grammar correction, vocabulary enhancement, pronunciation assessment, automated translation, text summarization, and content generation. Intelligent writing assistants support learners in producing grammatically accurate and stylistically appropriate texts while providing personalized feedback that enhances language development (Holmes *et al.,* 2022).

Generative AI systems have expanded these possibilities by assisting users in drafting reports, emails, research summaries, presentations, and creative content. Rather than replacing human communication, these technologies function as collaborative tools that improve efficiency, accuracy, and accessibility. Nevertheless, educators increasingly emphasize the importance of critical evaluation, originality, and responsible AI use to maintain academic integrity.

Mobile-Assisted Language Learning

The widespread availability of smartphones has transformed English language learning into a flexible and continuous process. Mobile learning applications enable learners to practice vocabulary, pronunciation, grammar, listening, and conversation skills anytime and anywhere. Features such as gamification, adaptive learning pathways, progress tracking, and immediate feedback increase learner motivation and engagement. Mobile learning also supports lifelong education by allowing professionals to update their communication skills while balancing work and personal commitments.

Virtual and Hybrid Learning

Virtual classrooms have become an integral component of higher education. Video conferencing platforms, cloud-based collaboration tools, and online learning environments facilitate synchronous and asynchronous communication among students and teachers. These environments encourage collaborative learning through group discussions, peer review, shared projects, and interactive presentations. Hybrid learning models combine classroom instruction with digital resources, offering greater flexibility while promoting learner-centered education.

Multimodal Communication

Digital transformation has encouraged the use of multimodal communication, integrating written language with images, infographics, videos, podcasts, and interactive presentations. Students increasingly communicate through multimedia assignments that require creativity, technological competence, and effective English expression. This shift reflects the communication practices commonly observed in contemporary workplaces and digital industries.

Artificial Intelligence and English Communication

Artificial Intelligence (AI) is transforming English communication by improving language learning, professional writing, and cross-cultural interaction through technologies such as natural language processing (NLP), machine learning, and speech recognition. AI-powered learning platforms offer personalized instruction by adapting to learners' proficiency levels and providing feedback on grammar, vocabulary, pronunciation, and writing (Luckin *et al.,* 2016).

Speech recognition and automated writing tools help learners improve pronunciation, grammar, and overall writing quality, while AI-assisted translation supports multilingual communication in education, business, and global collaboration. However, excessive dependence on AI may reduce learners' creativity, critical thinking, and independent writing skills. Ethical issues such as data privacy, algorithmic bias, and transparency also require careful attention. Therefore, UNESCO (2023) recommends a human-centered approach in which AI supports, rather than replaces, teachers and learners.

Digital Learning Technologies

Digital learning technologies have revolutionized English language education by creating interactive, collaborative, and learner-centered educational environments. Learning Management Systems such as Moodle, Canvas, and Google Classroom enable teachers to organize instructional materials, conduct assessments, monitor learner progress, and facilitate online discussions.

Cloud-based collaboration platforms including Google Workspace and Microsoft 365 support cooperative writing, peer editing, project-based learning, and document sharing. Students can jointly prepare presentations, reports, and research projects while receiving continuous feedback from teachers and peers. Such collaborative activities strengthen communication competence alongside digital literacy.

Educational applications incorporating gamification have further enhanced learner engagement. Interactive quizzes, badges, leaderboards, and adaptive challenges motivate learners to practice English regularly while maintaining high levels of participation. Video-based learning platforms, podcasts, digital storytelling applications, and virtual simulations create authentic communication experiences that improve listening, speaking, reading, and writing skills.

Virtual Reality (VR) and Augmented Reality (AR) represent emerging technologies with considerable potential for English language education. Immersive environments enable learners to participate in realistic communication scenarios such as interviews, conferences, business negotiations, and intercultural interactions. Experiential learning through virtual simulations improves confidence, fluency, and communicative competence while reducing language anxiety.

Social Media and Professional Communication

Social media has become an influential medium for English communication, connecting individuals across cultures and geographical boundaries. Platforms such as LinkedIn, YouTube, blogs, podcasts, and professional discussion forums facilitate knowledge sharing, networking, and collaborative learning. Learners increasingly engage with authentic English-language content produced by educators, researchers, journalists, and industry professionals.

In educational contexts, social media promotes collaborative learning by encouraging discussion, peer feedback, content creation, and reflective practice. Teachers use digital communities to share instructional resources, organize collaborative projects, and extend classroom learning beyond institutional boundaries.

Professional communication has also undergone significant transformation through digital networking platforms. Organizations rely on emails, video conferencing, collaborative software, project management applications, and enterprise communication systems to coordinate geographically dispersed teams. Effective communication in these environments requires concise writing, digital etiquette, intercultural competence, and professional English proficiency.

The growing influence of social media additionally requires learners to develop media literacy and ethical communication practices. Evaluating information credibility, avoiding misinformation, respecting digital privacy, and maintaining professional online identities have become essential competencies for responsible participation in digital society.

English Communication in Technology-Driven Workplaces

Contemporary workplaces increasingly depend on digital communication technologies to support organizational productivity and global collaboration. Remote work, hybrid employment models, virtual meetings, and cloud-based project management have transformed organizational communication practices. Employees communicate through emails, video conferences, instant messaging platforms, collaborative documents, and digital presentations, making English proficiency a critical professional skill.

Multinational organizations seek graduates who possess not only technical expertise but also advanced communication competencies. Effective professionals demonstrate the ability to prepare reports, deliver presentations, negotiate with international clients, collaborate within multicultural teams, and communicate persuasively across digital platforms. Consequently, English communication has become closely linked with employability, leadership, innovation, and organizational success.

Technology-driven workplaces also demand continuous learning. Professionals must regularly update their communication skills to adapt to evolving digital tools, AI-assisted workflows, and changing organizational practices. Lifelong learning, digital adaptability, and intercultural competence therefore remain fundamental attributes of successful professionals in the digital economy.

Challenges and Ethical Considerations

While digital transformation has significantly enhanced English communication and language education, it has also introduced several challenges and ethical concerns that require careful consideration. The integration of Artificial Intelligence (AI), digital communication platforms, and emerging educational technologies has improved accessibility, efficiency, and personalization of learning. However, these advancements have also generated complex issues related to equity, privacy, academic integrity, digital well-being, and the evolving role of educators. Addressing these challenges is essential to ensure that digital transformation contributes to inclusive, ethical, and sustainable educational development.

The Digital Divide and Educational Inequality

One of the most significant barriers to effective digital transformation is the digital divide, which refers to unequal access to digital devices, reliable internet connectivity, and technological infrastructure. Although online learning platforms and AI-powered educational tools have expanded learning opportunities, many students—particularly those in rural and economically disadvantaged communities—continue to experience limited access to these resources. Such disparities create unequal learning environments and hinder the development of English communication skills.

Educational inequality extends beyond physical access to technology. Differences in digital literacy, teacher preparedness, institutional infrastructure, and technological support further influence learners' ability to benefit from digital education. Governments and educational institutions must therefore invest in digital infrastructure, affordable internet access, teacher training, and inclusive educational policies to ensure equitable learning opportunities for all students.

Overdependence on Artificial Intelligence

Artificial Intelligence has transformed English language learning by providing automated feedback, grammar correction, personalized instruction, and content generation. Nevertheless, excessive reliance on AI tools may reduce learners' independent thinking, creativity, and writing proficiency. Students who depend entirely on AI-generated content may fail to develop essential language competencies such as critical reading, analytical writing, argumentation, and original expression.

AI should therefore be viewed as a complementary educational resource rather than a substitute for independent learning. Teachers should encourage learners to use AI for guidance, revision, and feedback while maintaining responsibility for original thinking and authentic communication. Human judgment remains essential in evaluating information, interpreting complex ideas, and producing meaningful academic discourse.

Academic Integrity and Plagiarism

Generative AI has created new challenges for academic integrity. AI-powered writing systems can produce essays, reports, summaries, and research content within seconds, raising concerns about plagiarism, authorship, and originality. Students may be tempted to submit AI-generated work without proper acknowledgement, thereby compromising ethical academic practices.

Educational institutions should establish clear policies regarding responsible AI use. Rather than prohibiting AI entirely, universities should teach students how to use AI ethically for brainstorming, language improvement, editing, and research support while emphasizing proper citation, transparency, and intellectual honesty. Assessment strategies should increasingly focus on critical thinking, oral presentations, project-based learning, reflective writing, and authentic performance tasks that encourage independent learning.

Data Privacy and Cybersecurity

Digital learning platforms collect substantial amounts of personal information, including academic records, communication data, assessment results, and behavioral analytics. AI-based educational systems often rely on learner data to provide personalized recommendations and adaptive instruction. Without appropriate safeguards, such information may be vulnerable to unauthorized access, misuse, or cyberattacks.

Educational institutions have an ethical responsibility to implement robust cybersecurity measures, transparent data management policies, and compliance with privacy regulations. Students should also receive digital citizenship education that develops awareness of online safety, responsible information sharing, password security, and ethical digital behavior.

Algorithmic Bias and Fairness

AI systems learn from existing datasets, which may contain cultural, linguistic, or social biases. Consequently, AI applications may unintentionally reinforce stereotypes or produce inaccurate evaluations of learners from diverse linguistic and cultural backgrounds. Such biases can influence automated assessment, language correction, recruitment processes, and communication technologies.

Developers, policymakers, and educational institutions should promote transparent, inclusive, and regularly evaluated AI systems. Ethical AI requires fairness, accountability, explainability, and continuous monitoring to ensure equitable educational outcomes for all learners regardless of their linguistic or cultural backgrounds.

Information Overload and Misinformation

The digital environment provides unprecedented access to information. While this abundance supports learning and research, it also exposes learners to misinformation, disinformation, and unreliable online content. Social media platforms frequently circulate unverified information, making critical evaluation an essential communication skill.

English language education should therefore integrate media literacy and information literacy into communication curricula. Learners must develop the ability to evaluate sources, verify information, distinguish facts from opinions, and communicate responsibly within digital environments.

Declining Interpersonal Communication

Although digital communication technologies facilitate global interaction, excessive dependence on virtual communication may reduce opportunities for face-to-face engagement. Interpersonal skills such as active listening, empathy, emotional intelligence, conflict resolution, and persuasive speaking remain essential components of effective communication. Educational institutions should therefore maintain a balanced approach that combines digital learning with collaborative classroom activities, discussions, debates, presentations, and interpersonal communication exercises.

Recommendations

The successful integration of digital transformation into English communication requires collaborative efforts from educational institutions, policymakers, technology developers, teachers, and learners. The following recommendations may strengthen English language education and professional communication in the digital era.

1. Integrate Digital Literacy into English Language Curriculum

English language curricula should combine linguistic competence with digital communication skills, information literacy, media literacy, and AI literacy. Learners should develop the ability to communicate effectively through diverse digital platforms while understanding ethical responsibilities associated with technology use.

2. Promote Responsible and Ethical Use of Artificial Intelligence

Educational institutions should formulate clear policies governing AI-assisted learning. Teachers should encourage responsible use of AI for feedback, editing, and personalized learning while discouraging academic dishonesty and excessive dependence on automated content generation.

3. Strengthen Teacher Professional Development

Teachers require continuous professional development to effectively integrate emerging technologies into English language instruction. Training programs should focus on AI applications, digital pedagogy, online assessment, instructional design, cybersecurity awareness, and innovative teaching methodologies.

4. Reduce the Digital Divide

Governments and institutions should improve digital infrastructure by expanding internet connectivity, providing affordable digital devices, and supporting technology access for underserved communities. Inclusive digital education is essential for reducing educational inequality.

5. Encourage Active and Collaborative Learning

Student-centered pedagogies such as project-based learning, collaborative writing, peer assessment, virtual exchanges, and interdisciplinary projects promote communication competence while developing teamwork, creativity, and problem-solving abilities.

6. Foster Intercultural Communication Competence

Since English functions as a global lingua franca, learners should be prepared to communicate respectfully with individuals from diverse cultural and linguistic backgrounds. Cross-cultural awareness, inclusivity, empathy, and ethical communication should become integral components of English language education.

7. Enhance Assessment Practices

Traditional examinations should be complemented by authentic assessments such as digital portfolios, presentations, case studies, workplace simulations, collaborative projects, reflective journals, and communication-based performance assessments that evaluate practical language use.

8. Promote Lifelong Learning

Given the rapid pace of technological change, continuous learning has become indispensable. Educational institutions should encourage learners to engage in self-directed learning, online certification programs, professional development courses, and continuous language improvement throughout their careers.

Conclusion

Digital transformation has significantly reshaped English communication by integrating technologies such as Artificial Intelligence, cloud computing, mobile applications, and digital collaboration platforms into education and professional communication. These innovations have enhanced language learning, personalized instruction, global connectivity, and the development of digital literacy and employability skills.

However, challenges such as the digital divide, overreliance on AI, data privacy, academic integrity, and ethical concerns require careful attention. Therefore, a balanced, human-centered approach is essential, where technology supports rather than replaces critical thinking, creativity, and effective communication. By promoting responsible innovation and lifelong learning, educational institutions can prepare learners to communicate confidently and succeed in the global digital era.

References

1. Alharbi, M. A. (2023). Artificial intelligence in English language teaching: Opportunities, challenges, and future directions. *Education and Information Technologies, 28*(12), 15673–15695.

2. Bates, A. W. (2022). *Teaching in a digital age: Guidelines for designing teaching and learning* (3rd ed.). Tony Bates Associates.
3. Holmes, W., Bialik, M., & Fadel, C. (2019). *Artificial intelligence in education: Promises and implications for teaching and learning*. Center for Curriculum Redesign.
4. Luckin, R., Holmes, W., Griffiths, M., & Forcier, L. B. (2016). *Intelligence unleashed: An argument for AI in education*. Pearson.
5. Organisation for Economic Co-operation and Development. (2021). *Digital education outlook 2021: Pushing the frontiers with AI, blockchain and robots*. OECD Publishing.
6. United Nations Educational, Scientific and Cultural Organization. (2023). *Guidance for generative AI in education and research*. UNESCO.
7. Vial, G. (2019). Understanding digital transformation: A review and a research agenda. *The Journal of Strategic Information Systems, 28*(2), 118–144. https://doi.org/10.1016/j.jsis.2019.01.003
8. World Economic Forum. (2023). *The future of jobs report 2023*. World Economic Forum.
9. Zawacki-Richter, O., Marín, V. I., Bond, M., & Gouverneur, F. (2019). Systematic review of research on artificial intelligence applications in higher education. *International Journal of Educational Technology in Higher Education, 16*, Article 39. https://doi.org/10.1186/s41239-019-0171-0

FUTURE ENERGY TECHNOLOGIES FOR CARBON-NEUTRAL SOCIETIES

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Abstract

The transition toward carbon-neutral societies has become one of the foremost global priorities in addressing climate change, energy security and sustainable development. Rising greenhouse gas emissions from fossil fuel-based energy systems have intensified the need for innovative clean energy technologies capable of reducing carbon footprints while supporting economic growth. Future energy technologies including renewable energy systems, green hydrogen production, advanced battery storage, smart electrical grids, carbon capture, utilization and storage (CCUS), nuclear innovations, artificial intelligence (AI)-enabled energy management and circular energy systems offer transformative pathways toward achieving net-zero emissions. This chapter provides a comprehensive overview of emerging energy technologies that are reshaping modern power generation, transmission, storage and consumption. It discusses technological advancements, policy frameworks, economic feasibility, environmental impacts and digital innovations that enable sustainable energy transitions. The chapter also examines challenges associated with infrastructure development, energy storage limitations, critical mineral dependency, financing mechanisms and policy implementation. Finally, future research directions and strategic recommendations are presented to accelerate global decarbonization and support resilient carbon-neutral societies. The integration of multidisciplinary technologies and international cooperation will be critical for ensuring affordable, reliable, and sustainable clean energy systems in the coming decades.

Keywords: Carbon Neutrality, Renewable Energy, Green Hydrogen, Smart Grids, Battery Energy Storage, Artificial Intelligence, Carbon Capture, Sustainable Energy, Net-Zero Emissions, Circular Economy.

1. Introduction

Climate change has emerged as one of the greatest environmental challenges of the twenty-first century. The continued dependence on fossil fuels including coal, petroleum, and natural gas has significantly increased atmospheric concentrations of greenhouse gases (GHGs), particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). According to the Intergovernmental Panel on Climate Change (IPCC), anthropogenic emissions are responsible for the increasing frequency of extreme weather events, rising global temperatures, sea-level rise, biodiversity loss, and ecosystem degradation. Consequently, governments, industries, and research institutions worldwide have committed to achieving carbon neutrality by mid-century through the deployment of advanced clean energy technologies.

Carbon neutrality refers to balancing greenhouse gas emissions through emission reduction strategies and carbon removal technologies. Achieving this goal requires a complete transformation of existing energy systems, replacing conventional fossil fuel-based infrastructure with renewable and low-carbon alternatives. Future energy technologies encompass not only renewable electricity generation but also intelligent energy management, advanced storage systems, hydrogen economies, digital energy networks, and carbon-negative technologies that collectively contribute to sustainable development.

This chapter explores the latest developments in future energy technologies and their role in supporting carbon-neutral societies. The discussion integrates engineering innovations, environmental considerations, economic perspectives, and policy frameworks to provide a holistic understanding of sustainable energy transitions.

2. Global Energy Transition toward Carbon Neutrality

The global commitment to carbon neutrality is reshaping energy policies and technological innovation. International agreements such as the Paris Agreement encourage countries to limit global warming by reducing greenhouse gas emissions and increasing renewable energy deployment.

Major drivers include

- Increasing energy demand
- Climate change mitigation
- Declining renewable energy costs
- Electrification of transportation
- Industrial decarbonization
- Digital transformation
- Government incentives
- Energy security

Several nations have announced net-zero emission targets between 2045 and 2070, leading to unprecedented investments in renewable infrastructure and clean technologies.

3. Emerging Renewable Energy Technologies

3.1 Solar Energy Innovations

Solar photovoltaic technology continues to dominate renewable electricity generation.

Recent developments include

- Perovskite solar cells
- Tandem photovoltaic modules
- Floating solar farms
- Building-integrated photovoltaics (BIPV)

- Agrivoltaic systems
- Transparent solar panels

Modern perovskite-silicon tandem cells have achieved efficiencies exceeding 30%, demonstrating remarkable progress compared to traditional silicon modules.

Advantages

- Zero operational emissions
- Low maintenance
- Modular deployment
- Rapid scalability

3.2 Advanced Wind Energy

Wind technology has evolved substantially through larger turbines, offshore installations, and floating platforms.

Emerging innovations include

- Floating offshore wind farms
- Vertical-axis turbines
- AI-based predictive maintenance
- Digital twins
- Blade recycling technologies

Offshore wind offers higher capacity factors and more consistent electricity generation than many onshore systems.

3.3 Hydropower Modernization

Modern hydropower focuses on sustainability rather than large reservoirs.

Technologies include

- Small hydropower
- Pumped hydro storage
- Fish-friendly turbines
- Sediment management systems

Pumped hydro remains the largest large-scale electricity storage technology worldwide.

4. Green Hydrogen Technologies

Green hydrogen is produced using renewable electricity through water electrolysis.

Major electrolyzer technologies include

- Alkaline Electrolysis
- PEM Electrolysis
- Solid Oxide Electrolysis

Applications include

- Steel manufacturing

- Fertilizer production
- Heavy transportation
- Aviation fuels
- Long-duration energy storage

Hydrogen can significantly reduce emissions from difficult-to-electrify sectors.

5. Advanced Energy Storage Technologies

Reliable storage is essential for integrating intermittent renewable resources.

Battery Technologies

- Lithium-ion batteries
- Sodium-ion batteries
- Solid-state batteries
- Zinc-air batteries
- Flow batteries

Mechanical Storage

- Pumped hydro
- Compressed air energy storage
- Flywheel storage

Thermal Energy Storage

- Molten salt
- Phase change materials
- Underground thermal storage

Advanced battery technologies are expected to improve energy density, safety, lifespan, and recyclability.

6. Smart Grids and Digital Energy Systems

Digitalization enables intelligent energy management through real-time monitoring and automation.

Major enabling technologies include

- Artificial Intelligence
- Machine Learning
- Internet of Things
- Digital Twins
- Blockchain
- Big Data Analytics
- Cloud Computing

Applications include

- Demand response

- Predictive maintenance
- Fault detection
- Renewable forecasting
- Energy optimization

Smart grids improve energy reliability while reducing transmission losses.

7. Carbon Capture, Utilization and Storage (CCUS)

CCUS technologies remove CO_2 from industrial emissions before atmospheric release.

Major approaches include

- Post-combustion capture
- Pre-combustion capture
- Oxy-fuel combustion
- Direct Air Capture (DAC)

Captured carbon can be

- Stored underground
- Converted into fuels
- Used in concrete production
- Used in chemicals manufacturing

Although CCUS remains costly, continued innovation is reducing implementation barriers.

8. Nuclear Energy for Carbon Neutrality

Advanced nuclear systems provide reliable low-carbon electricity.

Emerging technologies include

- Small Modular Reactors (SMRs)
- Generation IV reactors
- Molten salt reactors
- Fast breeder reactors
- Fusion energy research

These systems aim to improve safety, reduce waste, and enhance fuel efficiency.

9. Artificial Intelligence in Future Energy Systems

AI is transforming modern energy infrastructure.

Applications include:

- Renewable energy forecasting
- Grid optimization
- Battery health monitoring
- Predictive maintenance
- Intelligent building management
- Electric vehicle charging optimization

Machine learning algorithms significantly improve operational efficiency while minimizing energy waste.

10. Circular Economy in Energy Systems

Carbon neutrality requires efficient resource utilization throughout energy system life cycles. Circular approaches include

- Solar panel recycling
- Battery recycling
- Wind blade recycling
- Critical mineral recovery
- Waste-to-energy technologies

These strategies reduce environmental impacts while conserving valuable raw materials.

11. Challenges and Future Prospects

Despite remarkable progress, several barriers remain

Technical Challenges

- Renewable intermittency
- Energy storage limitations
- Grid modernization
- Critical mineral supply

Economic Challenges

- High capital investment
- Financing constraints
- Technology commercialization

Environmental Challenges

- Land use
- Biodiversity impacts
- Electronic waste
- Water consumption

Future research should focus on integrated renewable systems, AI-enabled energy optimization, low-cost hydrogen production, sustainable battery materials, advanced nuclear technologies, and large-scale carbon removal solutions.

Conclusion

Future energy technologies are fundamental to achieving carbon-neutral societies and mitigating the impacts of climate change. Renewable energy systems, green hydrogen, advanced storage technologies, smart grids, carbon capture, artificial intelligence, and circular economy practices collectively provide viable pathways toward sustainable development. While technical, economic, and policy challenges remain, rapid technological innovation and international collaboration are accelerating the global transition to clean energy. Governments, industries, researchers, and communities must work together to develop resilient, affordable, and environmentally responsible energy systems. Continued investment in research, infrastructure, and workforce development will be essential to achieving net-zero emissions and ensuring energy security for future generations.

References

1. Intergovernmental Panel on Climate Change (IPCC). (2023). *Climate Change 2023: Synthesis Report*. Geneva, Switzerland: IPCC.
2. Fatih Birol. (2024). *World Energy Outlook 2024*. Paris, France: International Energy Agency (IEA).
3. Fatih Birol. (2024). *Net Zero Roadmap: A Global Pathway to Keep the 1.5°C Goal in Reach—2024 Update*. Paris, France: International Energy Agency.
4. Francesco La Camera. (2024). *World Energy Transitions Outlook 2024: 1.5°C Pathway*. Abu Dhabi, UAE: International Renewable Energy Agency (IRENA).
5. Inger Andersen. (2024). *Emissions Gap Report 2024*. Nairobi, Kenya: United Nations Environment Programme (UNEP).
6. REN21 Secretariat. (2024). *Renewables 2024 Global Status Report*. Paris, France: REN21.
7. Fatih Birol. (2024). *Global Hydrogen Review 2024*. Paris, France: International Energy Agency.
8. National Renewable Energy Laboratory (NREL). (2024). *Annual Technology Baseline (ATB) 2024*. Golden, CO: U.S. Department of Energy.
9. Simon Black, Ian W. H. Parry, Nate Vernon, & Dimitri Zenghelis. (2024). *State and Trends of Carbon Pricing 2024*. Washington, DC: World Bank.
10. International Atomic Energy Agency (IAEA). (2024). *Nuclear Technology Review 2024*. Vienna, Austria: IAEA.
11. International Renewable Energy Agency (IRENA). (2023). *Innovation Landscape for Smart Electrification*. Abu Dhabi, UAE: IRENA.
12. U.S. Department of Energy. (2024). *Hydrogen Program Plan 2024*. Washington, DC: U.S. Department of Energy.
13. European Commission. (2024). *Strategic Energy Technology (SET) Plan Progress Report*. Brussels, Belgium: European Commission.
14. Zhang, X., Shah, N., Papageorgiou, L. G., & Samsatli, S. (2023). Pathways toward carbon-neutral energy systems: A review of emerging technologies and integrated strategies. *Renewable and Sustainable Energy Reviews, 181*, 113338.
15. Liu, Z., Deng, Z., Davis, S. J., & Guan, D. (2023). Near-zero emission energy systems for sustainable development: Challenges and future perspectives. *Nature Energy, 8*(7), 645–658.

TECHNOLOGY, SOCIAL MEDIA, AND MENTAL HEALTH: PSYCHOLOGICAL PERSPECTIVE ON EMERGING CHALLENGES FOR THE NEXT DECADE

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The past two decades have witnessed an unprecedented digital transformation that has reshaped human communication, relationships, education, healthcare, and work. While technological innovations have enhanced connectivity and access to information, they have simultaneously introduced complex psychological challenges. Social media platforms, artificial intelligence, immersive technologies, and algorithm-driven environments are influencing cognition, emotional regulation, identity formation, interpersonal relationships, and overall psychological well-being. Understanding these emerging challenges is essential for psychologists, educators, policymakers, and mental health professionals.

1. Evolution of Technology and Human Behaviour

Technology has become an inseparable component of modern human life, fundamentally transforming the ways individuals communicate, learn, work, establish relationships, and construct their identities. Unlike previous technological innovations that primarily enhanced physical productivity, contemporary digital technologies have increasingly influenced psychological processes, including attention, memory, emotion regulation, motivation, decision-making, and social interaction. The rapid convergence of internet technologies, artificial intelligence (AI), wearable devices, and immersive virtual environments has created an ecosystem in which human behaviour is continuously shaped by digital experiences. Consequently, understanding the evolution of technology is essential for explaining contemporary patterns of psychological functioning and mental well-being.

The relationship between technology and human behaviour is reciprocal rather than deterministic. While technological innovations influence cognitive and social processes, human needs, motivations, and behaviours simultaneously shape technological development and adoption. Psychological theories suggest that individuals actively interpret, adapt to, and modify technological environments based on personal experiences, social contexts, and cultural expectations (Bandura, 1986). As digital technologies evolve, so do the behavioural patterns associated with them, requiring continuous psychological adaptation.

2. The Psychological Perspective on Digital Revolution

The Digital Revolution represents one of the most significant technological transformations since the Industrial Revolution. Beginning in the late twentieth century, advances in computing power, telecommunications, and internet connectivity fundamentally altered how information is created, stored, processed, and disseminated (Castells, 2010). Digital technologies gradually replaced traditional analogue systems, resulting in unprecedented access to information and global interconnectedness.

Initially, digital technologies primarily served educational, governmental, and industrial purposes. However, the widespread availability of personal computers, smartphones, and broadband internet transformed digital technology into an integral component of everyday life. Today, digital platforms facilitate communication, healthcare, banking, education, entertainment, and employment, making technology indispensable for personal and professional functioning.

From a psychological perspective, the Digital Revolution has altered several fundamental cognitive processes. The availability of vast online information has reduced dependence on long-term memory while increasing reliance on external digital storage, a phenomenon often described as *cognitive offloading* (Risko & Gilbert, 2016). Rather than memorizing factual information, individuals increasingly focus on locating information efficiently through search engines and digital databases.

Furthermore, constant digital connectivity has reshaped attentional processes. Smartphones, notifications, and multitasking environments frequently compete for cognitive resources, contributing to fragmented attention and increased cognitive switching. Experimental research suggests that frequent task switching is associated with reduced sustained attention, lower working memory performance, and diminished executive functioning (Ophir *et al.,* 2009). Although digital technologies enhance efficiency in many domains, excessive multitasking may impair deep cognitive processing required for complex learning and problem-solving.

The Digital Revolution has also transformed social behaviour by extending interpersonal interactions beyond geographical boundaries. Digital communication enables individuals to maintain relationships across cultures and time zones, participate in online communities, and access social support networks that were previously unavailable. At the same time, increased online interaction has altered traditional patterns of face-to-face communication, raising concerns regarding loneliness, reduced social skills, and emotional dependency on digital interactions (Turkle, 2017).

The psychological impact of the Digital Revolution therefore extends beyond technological convenience. It represents a profound shift in how individuals perceive information, regulate attention, construct relationships, and interact with society.

During the first generation of the World Wide Web during the 1990s , users were passive consumers who accessed websites created by organizations, educational institutions, governments, and businesses. Communication was predominantly unidirectional, with minimal opportunities for interaction or user-generated content. Psychologically, this promoted information acquisition rather than social engagement. Individuals primarily used the internet to retrieve educational materials, news, research findings, and reference information. Consequently, internet usage during this period was largely goal-directed and task-oriented, emphasizing knowledge acquisition rather than social identity formation.

The Era of Participation and Social Connectivity

The emergence technological advancement in twenty-first century marked a fundamental transformation in the relationship between humans and technology. Unlike earlier digital revolution, which emphasized passive information consumption, users today have become active creators, collaborators, and distributors of digital content. Social networking platforms, blogs, wikis, video-sharing websites, podcasts, and collaborative applications revolutionized communication by allowing individuals to participate directly in the creation of online communities.

This participatory internet fundamentally altered human social behaviour. Platforms such as Facebook, YouTube, Instagram, X (formerly Twitter), TikTok, and LinkedIn blurred the distinction between content producers and consumers, allowing virtually anyone with internet access to communicate with global audiences. Digital participation became increasingly integrated into identity development, self-expression, and interpersonal relationships. From a psychological perspective, this amplified the role of social reinforcement in shaping behaviour. Features such as "likes," comments, shares, followers, and notifications introduced immediate and measurable forms of social feedback. These digital cues became powerful reinforcers, influencing self-esteem, motivation, and behavioural choices. Research indicates that positive online feedback activates neural reward pathways similar to those involved in other rewarding experiences, reinforcing repeated engagement with social media platforms (Meshi *et al.,* 2015).

At the same time, this intensified opportunities for social comparison. Individuals are frequently exposed to carefully curated portrayals of others' achievements, lifestyles, and appearances. In digital environments, such comparisons are often upward, involving comparisons with idealized representations that may contribute to dissatisfaction, reduced self-esteem, body image concerns, anxiety, and depressive symptoms, particularly among adolescents and young adults. Hence, Psychological adaptation is seen as pertinent in order to cope around this significantly transformed digital world.

3. Psychological Adaptation to Emerging Technologies

Technological advancement has consistently required individuals to adapt cognitively, emotionally, and behaviourally to changing environments. Psychological adaptation refers to the dynamic process through which individuals modify their thoughts, behaviours, and emotional responses to effectively function within evolving technological environments (Rauthmann & Sherman, 2018). As discussed, individuals are no longer just passive users of technology but active participants within interconnected digital ecosystems where interactions occur simultaneously across physical and virtual spaces. Consequently, adaptation involves not only acquiring technical skills but also developing psychological competencies that facilitate effective engagement with increasingly complex digital environments.

- **Cognitive Adaptation:** One significant aspect of psychological adaptation is cognitive adaptation. The abundance of digital information has fundamentally altered information processing strategies. Rather than relying solely on memory, individuals increasingly engage in cognitive offloading by storing information externally through smartphones, cloud services, and digital applications (Risko & Gilbert, 2016). While this strategy reduces cognitive load and enhances efficiency, excessive dependence on external memory systems may diminish opportunities for deep learning, critical thinking, and long-term knowledge retention.
- **Emotional Adaptation:** Technological adaptation also encompasses emotional adaptation. Digital environments continuously expose individuals to emotionally salient content, including news, social media interactions, online conflicts, and algorithmically curated information. Frequent exposure to emotionally stimulating content may contribute to emotional fatigue, anxiety, fear of missing out (FoMO), and reduced emotional regulation (Przybylski *et al.,* 2013). Conversely, digital technologies can facilitate emotional resilience by providing access to online social support, telepsychology services, mindfulness applications, and mental health resources. Thus, psychological adaptation involves balancing the emotional demands and benefits associated with digital engagement.
- **Behavioural Adaptation:** Behavioural adaptation represents another essential component of technology use. The widespread adoption of smartphones and wearable technologies has reshaped daily routines, communication patterns, health behaviours, and work practices. Remote working environments, online education, digital banking, telemedicine, and smart-home technologies have become integrated into everyday life. Successfully navigating these environments requires behavioural flexibility, digital literacy, and the capacity to regulate technology use according to situational demands.

Importantly, adaptation is not uniform across individuals. Factors such as age, personality traits, digital literacy, socioeconomic status, educational opportunities, cultural values, and prior technological experience influence the effectiveness of adaptation.

4. Understanding Digital Behaviour Through Social Cognitive Theory

Social Cognitive Theory (SCT), proposed by Bandura (1986), provides a comprehensive theoretical framework for understanding how human behaviour develops through the reciprocal interaction of personal factors, behavioural patterns, and environmental influences. Unlike theories that conceptualize behaviour as solely determined by environmental stimuli or internal psychological processes, SCT emphasizes that individuals are active agents who continuously shape and are shaped by their environments. This reciprocal perspective is particularly relevant in contemporary digital ecosystems, where technology functions simultaneously as an environmental influence, a medium for social interaction, and a platform for behavioural expression. Social Cognitive Theory offers a valuable lens through which the psychological impact of emerging technologies can be understood.

Reciprocal Determinism in Digital Environments

A central concept of Social Cognitive Theory is reciprocal determinism, which proposes that behaviour, personal cognitive factors, and environmental influences interact continuously to influence one another (Bandura, 1986). Rather than viewing technology as an external force that passively determines behaviour, reciprocal determinism suggests that users actively influence digital environments while simultaneously being influenced by them.

Within social media platforms, for example, an individual's personality traits, interests, motivations, and previous online behaviours influence the type of content they consume and share. In turn, platform algorithms analyze these behavioural patterns and personalize content recommendations, advertisements, and social interactions. This personalized digital environment subsequently shapes future attitudes, emotional responses, and behaviours, creating a continuous feedback loop between the individual and technology.

For instance, an adolescent who frequently views fitness-related content may receive increasingly appearance-focused recommendations through algorithmic curation. Continuous exposure to such content may strengthen body image concerns, reinforce social comparison, and encourage greater engagement with appearance-oriented communities. Conversely, individuals who actively engage with educational, health-promoting, or prosocial content may experience positive reinforcement that supports learning, self-improvement, and psychological well-being. Thus, digital behaviour emerges from an ongoing interaction between personal characteristics, behavioural choices, and technological environments.

Observational Learning and Digital Modelling

Observational learning, also known as modelling, represents another fundamental principle of Social Cognitive Theory. According to Bandura (1986), individuals acquire new behaviours by observing the actions of others and the consequences associated with those behaviours. Digital technologies have substantially expanded opportunities for observational learning by providing constant exposure to influencers, celebrities, peers, educators, and virtual communities across multiple platforms.

Unlike traditional learning environments, digital platforms enable individuals to observe thousands of behavioural models daily. These models demonstrate behaviours related to lifestyle choices, health practices, emotional expression, political beliefs, consumer behaviour, academic achievement, and interpersonal relationships. Successful or socially rewarded behaviours are particularly likely to be imitated because individuals perceive them as effective or desirable.

Social media influencers exemplify this process. Influencers who receive high levels of engagement through likes, comments, shares, and followers become salient behavioural models. Observing these forms of social reinforcement may motivate users to imitate similar behaviours in pursuit of comparable social approval. Consequently, trends involving fashion, dieting, exercise routines, consumer purchasing, communication styles, and even mental health disclosures spread rapidly through observational learning mechanisms. Observational learning also has positive implications. Online educational platforms enable students to observe expert demonstrations, healthcare professionals' model healthy behaviours, and psychologists disseminate evidence-based coping strategies through digital media. Consequently, technology serves as a powerful medium for both adaptive and maladaptive behavioural learning depending on the characteristics of the observed models.

Self-Efficacy in the Digital Age

Among the most influential constructs within Social Cognitive Theory is self-efficacy, defined as an individual's belief in their capability to organize and execute actions necessary to achieve desired outcomes (Bandura, 1997). Self-efficacy influences motivation, persistence, resilience, emotional regulation, and behavioural performance across numerous domains.

Within digital environments, digital self-efficacy has emerged as a critical determinant of successful technology adoption. Individuals who possess greater confidence in their ability to use digital technologies effectively are more likely to engage in online learning, telemedicine, virtual collaboration, digital financial services, and health-related technologies. Conversely, individuals with lower digital self-efficacy often experience anxiety, avoidance, and reduced engagement with technological innovations. Mastery experiences remain the strongest source of digital self-efficacy. Successfully navigating new software, participating in online education, or effectively using wearable health technologies enhances confidence and promotes future engagement.

Vicarious experiences, verbal encouragement, and reduced technological anxiety further strengthen digital self-efficacy by increasing individuals' confidence in managing unfamiliar technological environments. Digital self-efficacy also influences online safety behaviours. Individuals who believe they can critically evaluate online information are less susceptible to misinformation, phishing attacks, and fraudulent digital practices. Thus, enhancing digital self-efficacy represents an important objective for educators, policymakers, and mental health professionals seeking to promote responsible technology use.

Self-Regulation and Digital Well-being

Self-regulation constitutes another essential component of Social Cognitive Theory. It refers to the capacity to monitor, evaluate, and modify one's behaviour according to personally established goals and standards (Bandura, 1986). In contemporary digital environments, self-regulation has become increasingly important because digital platforms are intentionally designed to maximize user engagement through persuasive technologies, personalized algorithms, infinite scrolling, and variable reward schedules. Individuals with effective self-regulatory skills establish boundaries regarding screen time, manage online distractions, critically evaluate digital information, and balance virtual activities with offline responsibilities. Such individuals are more likely to engage in intentional rather than habitual technology use, thereby reducing the risk of problematic smartphone use, excessive social media engagement, and digital addiction.

Conversely, poor self-regulation has been associated with compulsive checking behaviours, disrupted sleep, procrastination, diminished academic performance, and increased psychological distress. Digital platforms frequently provide immediate rewards in the form of notifications, likes, and social feedback, making self-regulation particularly challenging. Consequently, interventions that strengthen goal setting, self-monitoring, and emotional regulation may improve digital well-being and promote healthier technology use.

Social Cognitive Theory as a Framework for Understanding Emerging Technologies

Thus, Social Cognitive Theory provides an integrative framework for understanding how individuals adapt to rapidly evolving technological environments. Rather than portraying technology as inherently beneficial or harmful, the theory emphasizes that technological outcomes depend on the dynamic interaction between environmental opportunities, cognitive processes, behavioural choices, and social influences. Emerging technologies such as artificial intelligence, virtual reality, wearable devices, and immersive digital platforms create novel learning environments in which observational learning, self-efficacy, reciprocal determinism, and self-regulation continuously shape behavioural outcomes.

5. Application of Social Cognitive Theory to Digital Behaviour

Social Cognitive Theory provides a comprehensive conceptual framework for understanding digital behaviour by emphasizing the dynamic interaction among personal factors, behaviour, and environmental influences. In the context of emerging technologies, digital platforms function as social environments where individuals continuously observe, imitate, evaluate, and regulate their behaviour. Social media platforms create environments that not only respond to users' behaviours but also shape future behavioural patterns through personalized algorithms and continuous feedback. Through the principle of reciprocal determinism, individuals actively influence their digital environments while simultaneously being influenced by them. Observational learning occurs as users acquire attitudes, behaviours, and social norms by observing peers, influencers, experts, and online communities. The development of digital self-efficacy influences individuals' confidence in using technology effectively, critically evaluating online information, and adapting to new digital innovations. Simultaneously, self-regulatory processes enable individuals to monitor screen time, control impulsive technology use, establish healthy digital boundaries, and engage with technology in ways that support their personal goals and psychological well-being. Consequently, the behavioural outcomes associated with technology use are neither inherently beneficial nor detrimental; rather, they depend on the interaction between individual cognitive processes, behavioural choices, and characteristics of the digital environment. Adaptive outcomes may include enhanced digital literacy, lifelong learning, social connectedness, improved access to healthcare, and psychological resilience, whereas maladaptive outcomes may involve problematic technology use, cyberbullying, social comparison, fear of missing out, sleep disturbances, anxiety, depression, and reduced psychological well-being. Thus, Social Cognitive Theory offers a robust explanatory framework for understanding how emerging technologies influence human behaviour and highlights the importance of promoting digital self-efficacy, critical digital literacy, and self-regulatory competencies to foster healthy and responsible technology use in an increasingly digital society.

Conclusion

The evolution of digital technologies has fundamentally transformed human behaviour, reshaping how individuals communicate, learn, work, form relationships, and construct their identities. From the early information-focused era to the participatory environment, technological advancements have created increasingly complex digital ecosystems that influence cognitive, emotional, and social functioning. While these innovations offer unprecedented opportunities for connectivity, learning, healthcare access, and personal development, they also present challenges related to information overload, social comparison, digital dependency, privacy concerns, and psychological well-being. Understanding these behavioural changes requires a theoretical framework that accounts for the dynamic interaction between individuals and their technological environments. Social Cognitive Theory provides such a framework by emphasizing the reciprocal relationships among personal factors, behaviour, and environmental influences. Through processes such as observational learning, self-efficacy, and self-regulation, individuals actively engage with and adapt to digital environments rather than merely responding to them. The theory highlights that the psychological impact of technology is not determined by the technology itself but by how individuals perceive, utilize, and regulate their interactions within digital contexts.

As emerging technologies continue to evolve, fostering digital literacy, critical thinking, self-regulatory skills, and digital self-efficacy will become increasingly important for promoting healthy adaptation and psychological well-being. Future research should continue to examine the complex mechanisms through which technological environments influence behaviour, while policymakers, educators, and mental health professionals should work collaboratively to ensure that technological innovation supports human flourishing. Ultimately, understanding technology through the lens of Social Cognitive Theory enables a more balanced perspective that recognizes both the opportunities and challenges of living in an increasingly digital world.

References

1. Bandura, A. (2018). Toward a psychology of human agency: Pathways and reflections. *Perspectives on Psychological Science*, 13(2), 130–136.
2. Niu, L. (2021). Using Social Cognitive Theory to examine the effects of social media on psychological well-being. *Computers in Human Behavior*, 121, Article 106810.
3. Valkenburg, P. M., & Peter, J. (2013). The differential susceptibility to media effects model. *Journal of Communication*, 63(2), 221–243.
4. Zheng, Y., & Kou, Z. (2023). Digital self-efficacy and self-regulated learning in technology-enhanced environments: A social cognitive perspective. *Educational Technology Research and Development*, 71(4), 1521–1542.
5. Niu, L. (2021). Using Social Cognitive Theory to examine the effects of social media on psychological well-being. *Computers in Human Behavior*, 121, Article 106810.

ADDITIVE MANUFACTURING OF LIGHTWEIGHT MECHANICAL COMPONENTS

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Abstract
Additive Manufacturing (AM), commonly known as 3D printing, has transformed modern manufacturing by enabling the fabrication of lightweight mechanical components with complex geometries, reduced material wastage, and improved performance. Unlike conventional subtractive manufacturing processes, AM builds components layer by layer directly from digital models, allowing engineers to optimize structures for weight reduction while maintaining mechanical strength. This chapter discusses the principles, technologies, materials, design methodologies, applications, challenges, and future trends associated with additive manufacturing of lightweight mechanical components. Particular emphasis is placed on topology optimization, lattice structures, metal and polymer AM processes, aerospace and automotive applications, and sustainability aspects. The chapter also explores recent advances involving artificial intelligence and smart manufacturing integration in AM systems [1-4].

1. Introduction

The demand for lightweight mechanical components has increased rapidly in aerospace, automotive, biomedical, and energy industries. Reducing component weight improves fuel efficiency, lowers emissions, enhances performance, and minimizes material consumption [2]. Traditional manufacturing techniques such as machining, casting, and forging often face limitations in producing highly complex lightweight geometries. Additive Manufacturing (AM) overcomes these challenges by enabling layer-by-layer fabrication directly from computer-aided design (CAD) models [3]. AM offers exceptional design freedom, allowing the creation of internal channels, lattice structures, honeycomb patterns, and topology-optimized shapes that are difficult or impossible to manufacture conventionally [4]. These features significantly reduce mass while preserving structural integrity. Modern industries increasingly use AM for producing lightweight brackets, turbine blades, heat exchangers, biomedical implants, and automotive components [5]. Recent research demonstrates that AM components can reduce weight by 30–60% compared to conventionally manufactured parts while maintaining comparable mechanical performance [1].

2. Fundamentals of Additive Manufacturing

Additive Manufacturing refers to a group of manufacturing processes that create three-dimensional objects by depositing material layer by layer [2]. The process begins with a digital CAD model, which is sliced into thin layers using specialized software. The AM machine then fabricates the component sequentially [6].

2.1 Working Principle

The general AM workflow includes:

- CAD model generation
- STL file conversion
- Slicing into layers
- Material deposition or fusion
- Post-processing and finishing

The layer-by-layer approach eliminates extensive tooling requirements and allows highly customized designs [3].

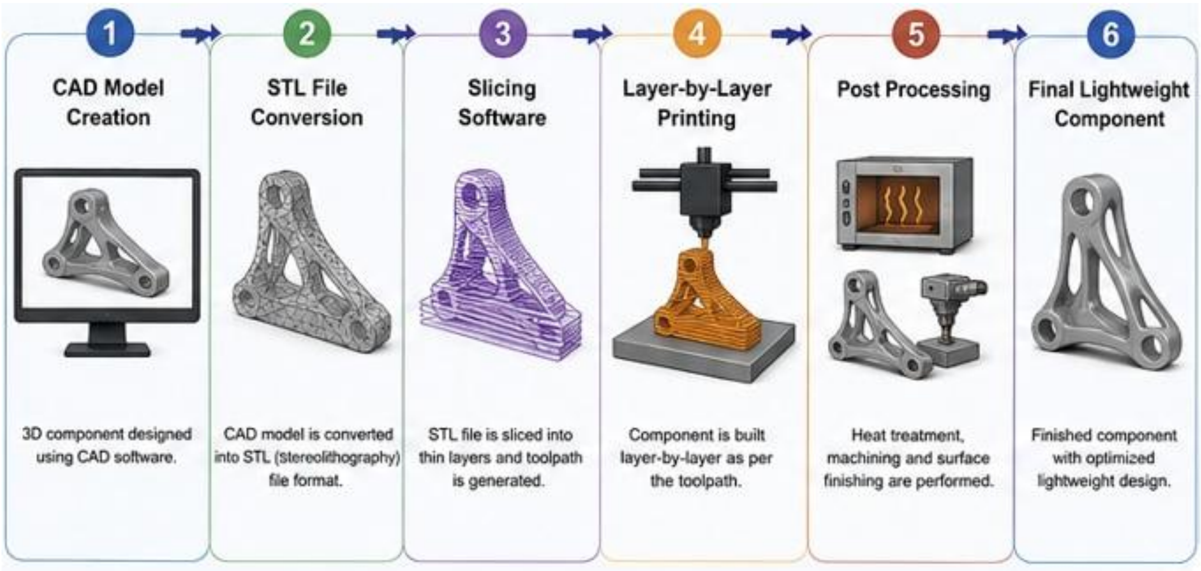

Figure 1: General workflow of the additive manufacturing process from CAD model to finished component.

2.2 Advantages of AM

- Reduced material wastage [4]
- Design flexibility [2]
- Shorter development cycle [5]
- Lightweight optimization [3]
- Reduced assembly requirements [1]
- Customization capability [6]
- Rapid prototyping and production [2]

2.3 Limitations of AM

Despite its advantages, AM still faces several limitations including high equipment cost, limited production speed, residual stress development, surface finish issues, and restricted build volume [5,6].

3. Lightweight Design Concepts in Additive Manufacturing

Lightweight design aims to reduce component mass without compromising functionality or strength [4].

3.1 Topology Optimization

Topology optimization distributes material only where required for load-bearing purposes. AM enables manufacturing of these optimized geometries effectively [4]. Optimized structures often resemble organic shapes and provide superior stiffness-to-weight ratios [7].

Benefits:

- Material savings
- Enhanced mechanical efficiency
- Improved energy absorption
- Lower manufacturing waste

Topology optimization has become an essential design methodology in aerospace and automotive engineering due to its ability to reduce component weight significantly [4,8].

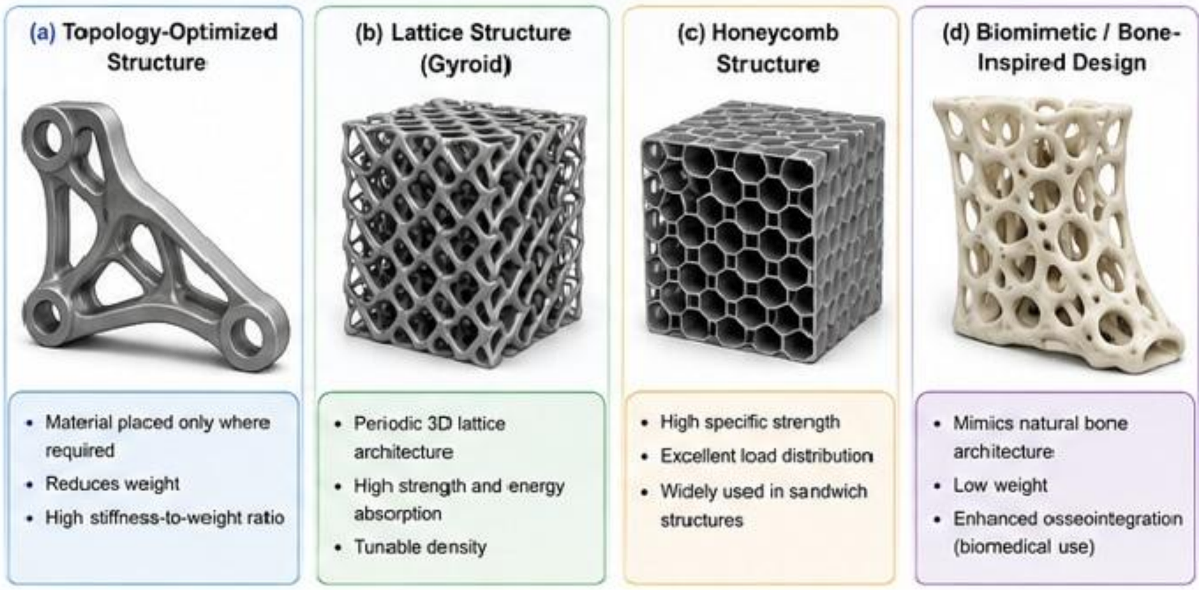

Figure 2. Lightweight design approaches used in additive manufacturing: (a) topology-optimized structure, (b) lattice structure, (c) honeycomb structure, and (d) biomimetic porous design

3.2 Lattice Structures

Lattice structures consist of repeating unit cells arranged in periodic or gradient patterns.

Common lattice structures include:

- Gyroid structures
- Honeycomb structures
- Octet truss lattices
- Kelvin cell structures

Gradient lattice structures provide variable density and improved mechanical performance [3].

3.3 Biomimetic Design

Nature-inspired designs imitate biological structures such as bones, shells, and honeycombs to achieve high strength with low mass [7]. Bone-like porous structures are widely studied in biomedical implant applications due to their excellent stiffness-to-weight characteristics [3].

4. Additive Manufacturing Technologies for Lightweight Components

Several AM technologies are used for manufacturing lightweight mechanical components.

4.1 Fused Deposition Modelling (FDM)

FDM extrudes thermoplastic filament through a heated nozzle [6].

Materials:

- PLA
- ABS
- Nylon
- Carbon-fiber reinforced polymers

Advantages:

- Low cost
- Easy operation
- Rapid prototyping

Limitations:

- Lower mechanical strength
- Surface finish issues

FDM is widely used for lightweight polymer structures and educational applications.

4.2 Selective Laser Melting (SLM)

SLM uses a high-energy laser to melt metal powders selectively [2].

Common Materials:

- Titanium alloys
- Aluminum alloys
- Stainless steel
- Inconel

SLM produces highly complex lightweight metallic components with excellent mechanical properties.

Applications include:

- Aerospace brackets
- Turbine components
- Medical implants

Studies indicate SLM can manufacture components with up to 63% weight reduction while maintaining high stiffness [9].

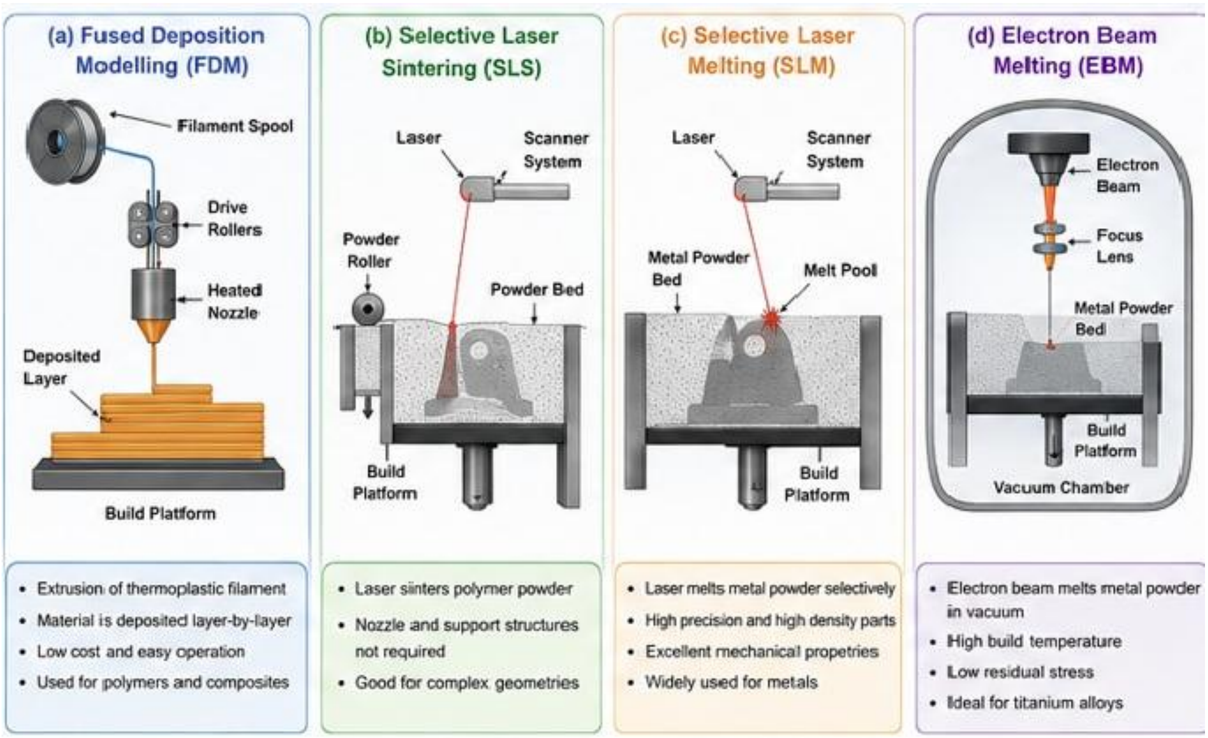

Figure 3: Schematic representation of major additive manufacturing technologies for lightweight component fabrication: (a) FDM, (b) SLS, (c) SLM, and (d) EBM.

4.3 Electron Beam Melting (EBM)

EBM uses an electron beam instead of a laser to melt metal powders under vacuum conditions.

Features:

- Reduced residual stress
- High build temperature
- Suitable for titanium alloys

EBM is extensively used in aerospace and biomedical industries [5].

4.4 Selective Laser Sintering (SLS)

SLS uses laser energy to sinter powdered polymers.

Advantages:

- No support structures required
- Good design freedom
- Lightweight polymer components

Applications:

- Functional prototypes
- Ducts and housings
- Automotive interiors

4.5 Directed Energy Deposition (DED)

DED deposits material while simultaneously melting it using laser or plasma energy[6].

Applications:

- Repair of aerospace components
- Large metallic structures
- Hybrid manufacturing

5. Materials Used in Additive Manufacturing

Material selection plays a critical role in lightweight component manufacturing[5].

5.1 Metallic Materials

Titanium Alloys

Titanium alloys such as Ti-6Al-4V provide:

- High strength-to-weight ratio
- Corrosion resistance
- Biocompatibility

Widely used in aerospace and biomedical sectors.

Aluminium Alloys

Aluminum alloys offer:

- Low density
- Good thermal conductivity
- Excellent machinability

Used extensively in automotive and aerospace structures.

Stainless Steel

Provides:

- Corrosion resistance
- Mechanical durability
- Ease of fabrication

5.2 Polymer Materials

Common polymers include:

- PLA
- ABS
- PEEK

- Nylon

Carbon-fiber reinforced polymers improve stiffness and reduce weight further [6].

5.3 Composite Materials

Composite AM materials combine:

- Polymer matrix
- Reinforcement fibers
- Ceramic particles

These materials offer superior mechanical performance and lightweight characteristics [5].

6. Mechanical Properties of AM Components

Mechanical properties depend strongly on:

- Build orientation
- Layer thickness
- Printing speed
- Temperature
- Material composition [2].

6.1 Strength and Stiffness

AM parts often exhibit anisotropic properties due to layer-by-layer fabrication.

Optimized parameters can produce components with mechanical properties approaching wrought materials [2,5].

6.2 Fatigue Performance

Fatigue behavior is influenced by:

- Surface roughness
- Internal porosity
- Residual stresses

Post-processing methods such as heat treatment and machining improve fatigue life [2].

6.3 Energy Absorption

Lattice structures produced through AM demonstrate excellent energy absorption properties useful in [8]:

- Crash structures
- Protective equipment
- Aerospace impact components

7. Applications of Lightweight AM Components

7.1 Aerospace Industry

The aerospace industry is among the largest adopters of AM [2].

Applications:

- Aircraft brackets
- Fuel nozzles
- Turbine blades
- Heat exchangers

Benefits include:

- Reduced fuel consumption
- Lower emissions
- Improved payload capacity

Aircraft manufacturers use topology-optimized AM parts to reduce overall aircraft weight significantly [4,9].

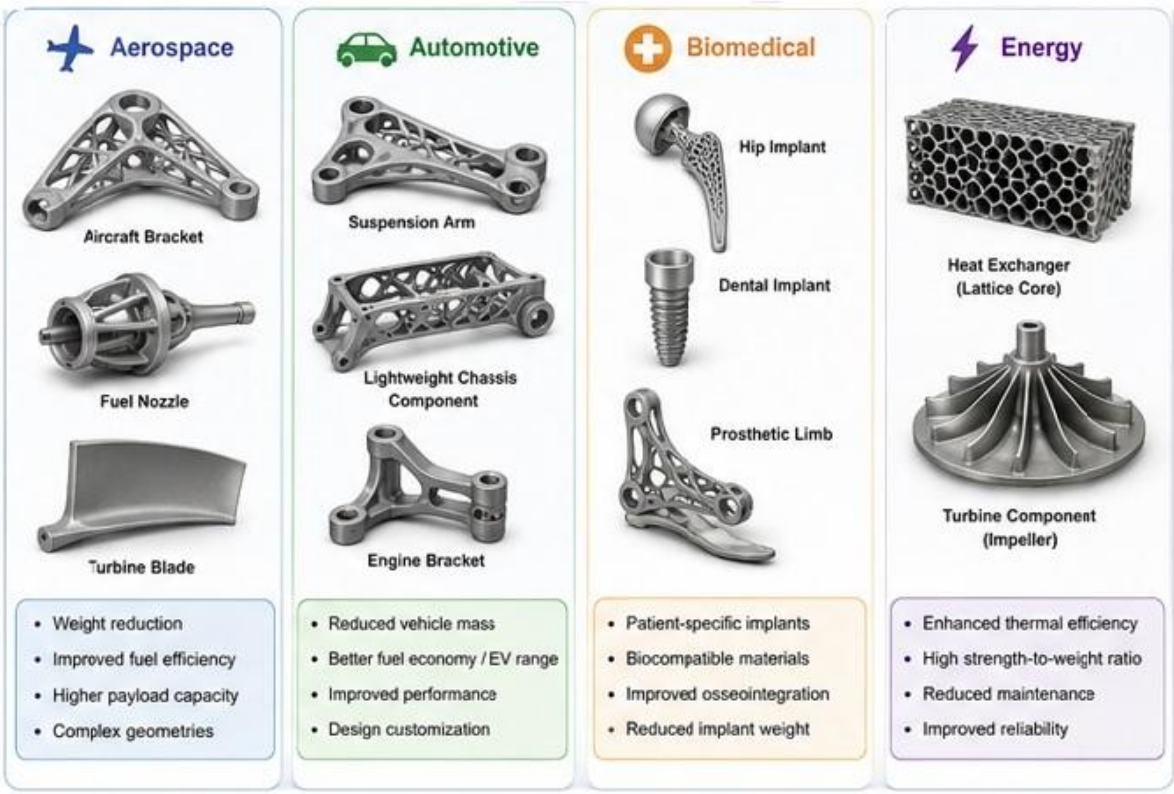

Figure 4. Industrial applications of lightweight additive-manufactured components in aerospace, automotive, biomedical, and energy sectors.

7.2 Automotive Industry

AM enables production of:

- Lightweight chassis components
- Suspension systems
- Engine parts
- Custom racing components

Reduced vehicle mass improves fuel economy, electric vehicle range, and acceleration performance [4].

7.3 Biomedical Industry

AM allows personalized lightweight implants.

Examples:

- Hip implants
- Dental implants
- Prosthetic limbs

Porous lattice structures improve Osseo integration and reduce implant weight[3].

7.4 Energy Sector

Applications include:

- Lightweight turbine components
- Heat exchangers
- Cooling systems

AM improves thermal efficiency and reduces maintenance costs.

8. Design for Additive Manufacturing (DfAM)

Design for Additive Manufacturing involves optimizing component geometry specifically for AM processes.

8.1 Key Principles

- Minimize support structures
- Optimize orientation
- Use lattice infill
- Consolidate assemblies
- Reduce stress concentrations

These principles improve manufacturability and mechanical performance [4].

8.2 Software Tools

Popular DfAM software includes:

- Autodesk Fusion 360
- ANSYS
- Altair Inspire
- nTopology

These tools integrate topology optimization and simulation capabilities [7]

9. Sustainability and Environmental Impact

AM contributes to sustainability through:

- Reduced material wastage

- Lightweight transportation systems
- Lower energy consumption
- Localized manufacturing

Conventional machining may waste up to 80% of raw material, whereas AM deposits material only where required. AM also supports distributed manufacturing and reduces transportation-related carbon emissions [5]. However, energy consumption during metal AM processes remains a challenge [2]. However, energy consumption during metal AM processes remains a challenge.

10. Challenges in Additive Manufacturing

Despite major advantages, AM faces several technical challenges [2,5,6].

10.1 Residual Stress and Distortion

Rapid heating and cooling cause:

- Warping
- Cracking
- Dimensional inaccuracies

10.2 Surface Finish

AM parts often require:

- Machining
- Polishing
- Heat treatment

10.3 Quality Assurance

Internal defects such as porosity are difficult to detect.

Advanced inspection techniques include:

- CT scanning
- Ultrasonic testing
- Optical metrology

10.4 Production Cost

Metal AM systems remain expensive due to:

- Powder costs
- Equipment costs
- Post-processing requirements

11. Future Trends in Additive Manufacturing

11.1 Artificial Intelligence Integration

AI and machine learning are increasingly used for:

- Process optimization
- Defect prediction

- Real-time monitoring

11.2 Multi-Material Printing

Future AM systems will combine multiple materials in a single component to achieve[5]:

- Variable stiffness
- Thermal management
- Functional grading

11.3 Smart Manufacturing

Industry 4.0 integration enables [10]:

- Digital twins
- Automated quality control
- Predictive maintenance

11.4 Large-Scale AM

Large-format AM systems are emerging for:

- Aerospace structures
- Construction components
- Marine applications

Conclusion

Additive Manufacturing has revolutionized the production of lightweight mechanical components by enabling unprecedented design freedom, material efficiency, and structural optimization. Technologies such as SLM, EBM, FDM, and SLS allow engineers to fabricate intricate geometries and lattice structures that significantly reduce weight while maintaining excellent mechanical performance [2,4]. Industries including aerospace, automotive, biomedical, and energy increasingly rely on AM to improve efficiency, reduce emissions, and enhance functionality.

Despite challenges such as residual stresses, high costs, and quality assurance issues, ongoing advancements in materials, artificial intelligence, and smart manufacturing continue to improve AM capabilities [10]. Future developments in multi-material printing, topology optimization, and automated process monitoring are expected to further expand the role of additive manufacturing in next-generation lightweight engineering systems.

References

1. Kumar, M., & Shetty, M. (2025). Additive manufacturing for lightweight mechanical components: Techniques and applications. *Innovative Journal of Integrated Research and Technological Innovations.*

2. Lewandowski, J. J., & Seifi, M. (2016). Metal additive manufacturing: A review of mechanical properties. *Annual Review of Materials Research, 46*, 151–186. https://doi.org/10.1146/annurev-matsci-070115-032024
3. Seharing, A., Azman, A. H., & Abdullah, S. (2020). A review on integration of lightweight gradient lattice structures in additive manufacturing parts. *Advances in Mechanical Engineering, 12*(6). https://doi.org/10.1177/1687814020916951
4. Zhu, C., Liu, T., Qian, F., Chen, W., Chandrasekaran, S., Yao, B., Song, Y., Duoss, E. B., Kuntz, J. D., Spadaccini, C. M., Worsley, M. A., & Li, H. (2019). Review on design and structural optimisation in additive manufacturing: Towards next-generation lightweight structures. *Materials & Design, 183*, 108137. https://doi.org/10.1016/j.matdes.2019.108137
5. Li, J., Yang, T., Liu, S., Shi, Y., & Zhao, K. (2025). A review on recent progress in light metal solid-phase additive manufacturing. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture.*
6. Niu, X., Singh, S., Garg, A., *et al.* (2019). Review of materials used in laser-aided additive manufacturing processes to produce metallic products. *Frontiers of Mechanical Engineering, 14*(2), 282–298. https://doi.org/10.1007/s11465-019-0541-y
7. Wu, J., Aage, N., Westermann, R., & Sigmund, O. (2016). Infill optimization for additive manufacturing—Approaching bone-like porous structures. *IEEE Transactions on Visualization and Computer Graphics, 24*(2), 1127–1140. https://doi.org/10.1109/TVCG.2017.2655523
8. Ambekar, R. S., *et al.* (2022). Topologically engineered 3D printed architectures with superior mechanical strength.
9. Hilpert, E., *et al.* (2018). Precision manufacturing of a lightweight mirror body made by selective laser melting.
10. Karimzadeh, M., *et al.* (2023). Review of machine learning methods for additive manufacturing of functionally graded materials.

POLLUTION CONTROL THROUGH GREEN CHEMISTRY

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1. Introduction

Environmental pollution has become one of the greatest challenges facing humanity in the twenty-first century. Rapid industrialization, urbanization, excessive use of fossil fuels, and the manufacture of hazardous chemicals have resulted in severe contamination of air, water, and soil. Conventional methods of pollution control generally focus on treating waste after it has been produced. However, this approach is expensive and often transfers pollutants from one medium to another rather than eliminating them.

Green Chemistry offers a revolutionary solution by preventing pollution at its source. Instead of treating waste after it is generated, Green Chemistry aims to design chemical products and processes that reduce or eliminate the use and generation of hazardous substances. Introduced by Paul T. Anastas and John C. Warner in 1998, Green Chemistry has emerged as a sustainable approach to industrial development and environmental protection.

2. What is Pollution?

Pollution is the introduction of harmful substances or energy into the environment that adversely affects living organisms and natural ecosystems.

Major Types of Pollution

- Air Pollution
- Water Pollution
- Soil Pollution
- Noise Pollution
- Thermal Pollution
- Radioactive Pollution

Major Sources

- Chemical industries
- Agricultural activities
- Plastic waste
- Vehicle emissions
- Thermal power plants

- Domestic waste
- Mining activities

3. What is Green Chemistry?

Chemistry is defined as the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances.

According to the U.S. Environmental Protection Agency (EPA):

"Green Chemistry is the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances."

Green Chemistry focuses on pollution prevention rather than pollution treatment.

4. Principles of Green Chemistry

Paul Anastas and John Warner proposed 12 Principles of Green Chemistry.

1. Prevention

Prevent waste rather than treating or cleaning it after formation.

2. Atom Economy

Design reactions so that maximum atoms of reactants become part of the final product.

3. Less Hazardous Chemical Syntheses

Use safer reaction pathways.

4. Designing Safer Chemicals

Produce chemicals with minimal toxicity.

5. Safer Solvents and Auxiliaries

Replace toxic organic solvents with safer alternatives like water or ethanol.

6. Energy Efficiency

Carry out reactions at room temperature and atmospheric pressure whenever possible.

7. Use Renewable Feedstocks

Use renewable raw materials such as biomass instead of petroleum.

8. Reduce Derivatives

Avoid unnecessary protection and deprotection steps.

9. Catalysis

Use catalysts instead of stoichiometric reagents.

10. Design for Degradation

Products should break down into harmless substances after use.

11. Real-Time Analysis

Monitor reactions continuously to prevent hazardous by-products.

12. Inherently Safer Chemistry

Choose substances that minimize the possibility of accidents.

5. How Green Chemistry Controls Pollution

Green Chemistry controls pollution through prevention rather than remediation.

A. Prevention of Waste

Traditional industries produce large amounts of hazardous waste.

Green Chemistry minimizes waste generation by improving reaction efficiency.

Example:

Atom-efficient synthesis of ibuprofen reduced waste generation by nearly 80%.

B. Reduction of Toxic Chemicals

Hazardous chemicals are replaced with environmentally friendly alternatives.

Examples include:

- Water-based paints replacing solvent-based paints
- Lead-free pigments
- Mercury-free processes

C. Use of Renewable Resources

Green Chemistry encourages the use of:

- Vegetable oils
- Biomass
- Starch
- Cellulose
- Agricultural waste

These reduce dependence on fossil fuels.

D. Energy Conservation

Many chemical reactions require high temperatures and pressures.

Green Chemistry promotes:

- Microwave-assisted synthesis
- Ultrasound-assisted synthesis
- Photochemical reactions
- Biocatalysis

These techniques reduce energy consumption and greenhouse gas emissions.

E. Catalysis

Catalysts increase reaction efficiency without being consumed.

Benefits include:

- Higher yields
- Lower energy requirements
- Reduced waste

- Fewer by-products

Examples:

- Enzymes
- Zeolites
- Metal nanoparticles

F. Biodegradable Products

Products are designed to decompose naturally.

Examples:

- Biodegradable plastics
- Green detergents
- Eco-friendly pesticides

G. Carbon Dioxide Utilization

Instead of releasing CO_2 into the atmosphere, Green Chemistry converts it into useful products such as:

- Methanol
- Polycarbonates
- Carbonates

This helps reduce greenhouse gas emissions.

6. Industrial Applications

Pharmaceutical Industry

- Solvent-free synthesis
- Catalytic reactions
- Continuous manufacturing

Result:

- Less waste
- Reduced solvent consumption
- Lower production cost

Agriculture

Green Chemistry promotes:

- Biopesticides
- Biofertilizers
- Controlled-release fertilizers

Benefits:

- Less soil pollution
- Reduced groundwater contamination

Textile Industry

Uses:

- Enzyme-based bleaching
- Water-saving dyeing
- Natural dyes

Benefits:

- Reduced chemical discharge
- Lower water consumption

Polymer Industry

Development of:

- Bioplastics
- Compostable plastics
- Plant-based polymers

Examples:

- PLA
- PHA

Paper Industry

Green bleaching agents:

- Hydrogen peroxide
- Oxygen
- Ozone

instead of chlorine.

This reduces dioxin pollution.

7. Green Chemistry Techniques

Some important green chemistry techniques include:

Microwave-assisted synthesis

- Faster reactions
- Higher yield
- Lower energy use

Ultrasound-assisted synthesis

- Improved reaction rates
- Less solvent

Solvent-free reactions

- Eliminate volatile organic compounds (VOCs)

Supercritical CO_2 extraction

- Replaces harmful organic solvents

Biocatalysis

Uses enzymes for selective and environmentally friendly reactions.

8. Benefits of Green Chemistry

Environmental Benefits

- Reduced pollution
- Lower greenhouse gas emissions
- Cleaner air and water
- Conservation of natural resources

Economic Benefits

- Lower production costs
- Reduced waste treatment expenses
- Energy savings
- Improved process efficiency

Social Benefits

- Improved public health
- Safer workplaces
- Sustainable industrial development

9. Challenges

Although Green Chemistry offers many benefits, several challenges remain:

- High initial investment
- Limited awareness
- Lack of trained personnel
- High cost of green technologies
- Difficulty in replacing conventional industrial processes
- Limited availability of renewable raw materials

10. Future Prospects

The future of Green Chemistry is highly promising due to:

- Increasing environmental regulations
- Growing demand for sustainable products
- Advances in biotechnology
- Artificial intelligence in chemical process design
- Nanotechnology
- Circular economy practices

- Green manufacturing

Future research is expected to focus on zero-waste manufacturing, carbon-neutral chemical processes, biodegradable materials, and renewable energy integration.

Conclusion

Green Chemistry is a powerful and sustainable approach for controlling pollution by preventing the generation of hazardous substances rather than treating them after they are formed. Through safer chemicals, renewable feedstocks, energy-efficient processes, catalysis, and biodegradable products, Green Chemistry reduces environmental pollution while improving industrial efficiency and economic performance. Adopting Green Chemistry principles across industries, agriculture, pharmaceuticals, and education is essential for achieving sustainable development and protecting the environment for future generations.

References

1. Anastas, P. T., & Warner, J. C. (1998). *Green Chemistry: Theory and Practice*. Oxford University Press.
2. Anastas, P. T., & Zimmerman, J. B. (2018). *The Periodic Table of the Elements of Green Chemistry*. Green Chemistry, 20, 1929–1961.
3. United States Environmental Protection Agency (EPA). *Green Chemistry Program*.
4. Lancaster, M. (2016). *Green Chemistry: An Introductory Text* (3rd Edition). Royal Society of Chemistry.
5. Clark, J. H., & Macquarrie, D. J. (2002). *Handbook of Green Chemistry and Technology*. Blackwell Science.
6. Ahluwalia, V. K. (2019). *Green Chemistry*. Narosa Publishing House.

SENSORS AND SMART DETECTION SYSTEMS

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Abstract

Sensors and smart detection systems are fundamental technologies that enable the measurement, monitoring, and intelligent control of physical, chemical, and biological processes across modern scientific and engineering applications. This chapter introduces the basic concepts of sensors, transducers, and detectors, highlighting their operating principles, classifications, and performance characteristics. It discusses common sensing mechanisms, including resistive, capacitive, inductive, optical, and piezoelectric techniques, along with the essential role of signal conditioning and data acquisition in ensuring accurate and reliable measurements. The chapter further explores the evolution from conventional sensing devices to smart sensors equipped with embedded processing, self-calibration, and communication capabilities, enabling intelligent detection and autonomous decision-making. The integration of microcontroller-based sensing, Internet of Things (IoT) technologies, and wireless sensor networks is presented as a key driver of real-time monitoring, remote automation, and connected systems. Major application areas including industrial automation, healthcare and wearable devices, environmental monitoring, and smart homes and energy systems demonstrate the transformative impact of intelligent sensing technologies on productivity, safety, sustainability, and quality of life. Finally, the chapter examines emerging trends such as microelectromechanical systems (MEMS), nanosensors, artificial intelligence (AI)-enabled sensing, and edge intelligence, while addressing critical challenges related to calibration, reliability, cybersecurity, and system resilience. Together, these developments illustrate how smart detection systems are shaping the next generation of intelligent, interconnected technologies and supporting the advancement of transformative science and technology.

Introduction to Sensors and Detection Systems

Definition of Sensors, Transducers, and Detectors

Sensors, transducers, and detectors are fundamental components in modern measurement and detection systems, each serving distinct but interconnected roles. A sensor is a device that responds to a physical stimulus such as temperature, pressure, or light and converts it into a measurable signal, often electrical [2]. Transducers, closely related to sensors, specifically refer to devices that convert one form of energy into another, enabling the translation of physical phenomena into usable electrical signals for analysis or control. Detectors, meanwhile, are specialized devices designed to identify the presence or absence of a particular physical quantity or substance, often triggering a response or alert [1]. Together, these components form the backbone of detection systems, facilitating accurate monitoring and control across diverse scientific and technological applications.

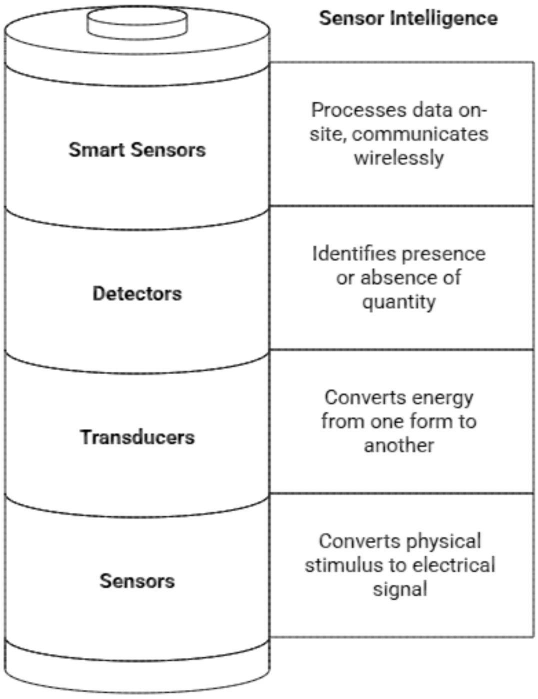

Figure 1: Sensor evolution from basic to intelligent detection

Importance in Science, Engineering and Everyday Life

Sensors, transducers, and detectors play a crucial role in science, engineering, and everyday life by enabling precise measurement, monitoring, and control of physical phenomena. In scientific research, they provide accurate data essential for experiments and observations, driving advancements in knowledge and technology. In engineering, these devices are integral to designing automated systems, ensuring safety, efficiency, and reliability in processes ranging from manufacturing to aerospace [2]. Everyday applications include environmental monitoring, healthcare diagnostics, and consumer electronics, where these components enhance convenience, safety, and quality of life. Their widespread importance underscores the continuous evolution of detection technologies as foundational tools shaping transformative innovations across multiple domains.

Evolution From Conventional to Smart Sensors

The evolution from conventional to smart sensors marks a significant advancement in detection technology, driven by the integration of microelectronics, signal processing, and communication capabilities. Conventional sensors primarily focus on detecting and converting physical stimuli into electrical signals, often requiring external processing units for data interpretation and decision-making. In contrast, smart sensors incorporate embedded microprocessors or digital signal processors that enable on-site data processing, self-calibration, diagnostics, and adaptive responses. This transformation enhances sensor accuracy, reliability, and functionality while reducing system complexity and power consumption. Smart sensors also facilitate real-time data communication and integration into larger networks, supporting the development of the Internet of Things (IoT) and advanced automation systems [4]. This progression reflects the broader trend in science and technology toward intelligent, interconnected devices that enable more sophisticated monitoring, control, and predictive capabilities across diverse applications.

Principles and Characteristics of Sensors

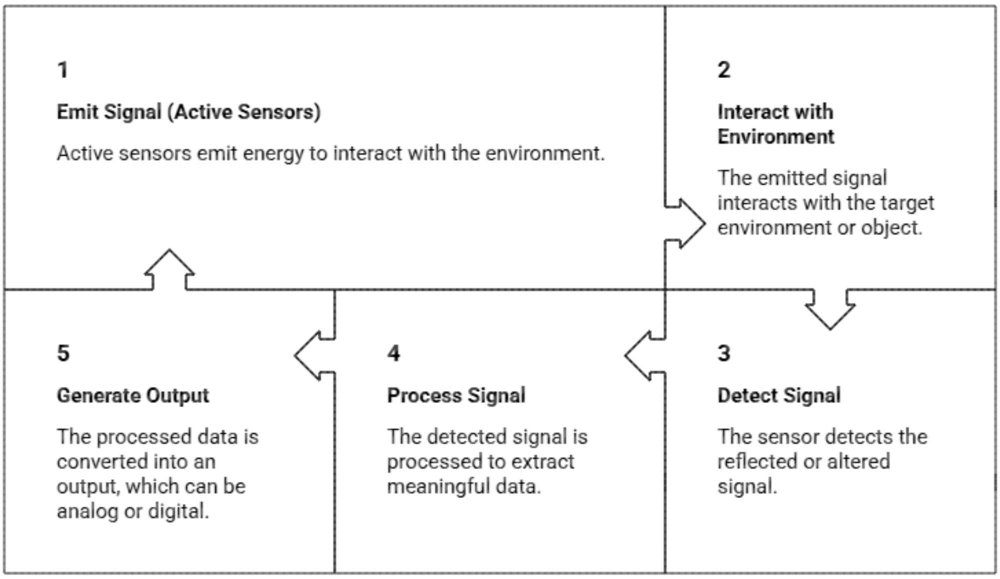

Figure 2: Sensor operation cycle

Basic Sensing Mechanisms (Resistive, Capacitive, Inductive, Optical, Piezoelectric)

Basic sensing mechanisms form the foundation of sensor technology, enabling the conversion of physical stimuli into measurable signals through distinct physical principles. Resistive sensing relies on changes in electrical resistance caused by variations in temperature, strain, or chemical composition, making it widely used in temperature sensors and strain gauges. Capacitive sensing measures changes in capacitance due to variations in distance, dielectric properties, or surface contact, commonly applied in touchscreens and proximity sensors. Inductive sensing detects changes in inductance influenced by the presence of metallic objects or magnetic fields, often utilized in metal detectors and position sensors. Optical sensing employs light interaction such as absorption, reflection, or emission to detect changes in environmental conditions or material properties, integral to fibre optic sensors and photodetectors. Piezoelectric sensing exploits the generation of electric charge in certain materials under mechanical stress, enabling precise detection of pressure, acceleration, and vibration [2]. Together, these mechanisms underpin a wide array of sensor designs, supporting the diverse requirements of transformative science and technology by providing accurate, reliable, and responsive measurement capabilities.

Performance Characteristics: Sensitivity, Accuracy, Precision, Range, and Response Time

Performance characteristics of sensors are sensitivity, accuracy, precision, range and response time are critical parameters defining their effectiveness and suitability for specific applications.

Sensitivity refers to the sensor's ability to detect small changes in the measured quantity. It is defined as the ratio of the change in output signal to the change in input stimulus.

High sensitivity implies that even minor variations in the physical parameter produce significant changes in output, enhancing detectability.

Accuracy indicates how close the sensor's output is to the true value of the measured quantity. It is often expressed as the difference between the measured value and the true value.

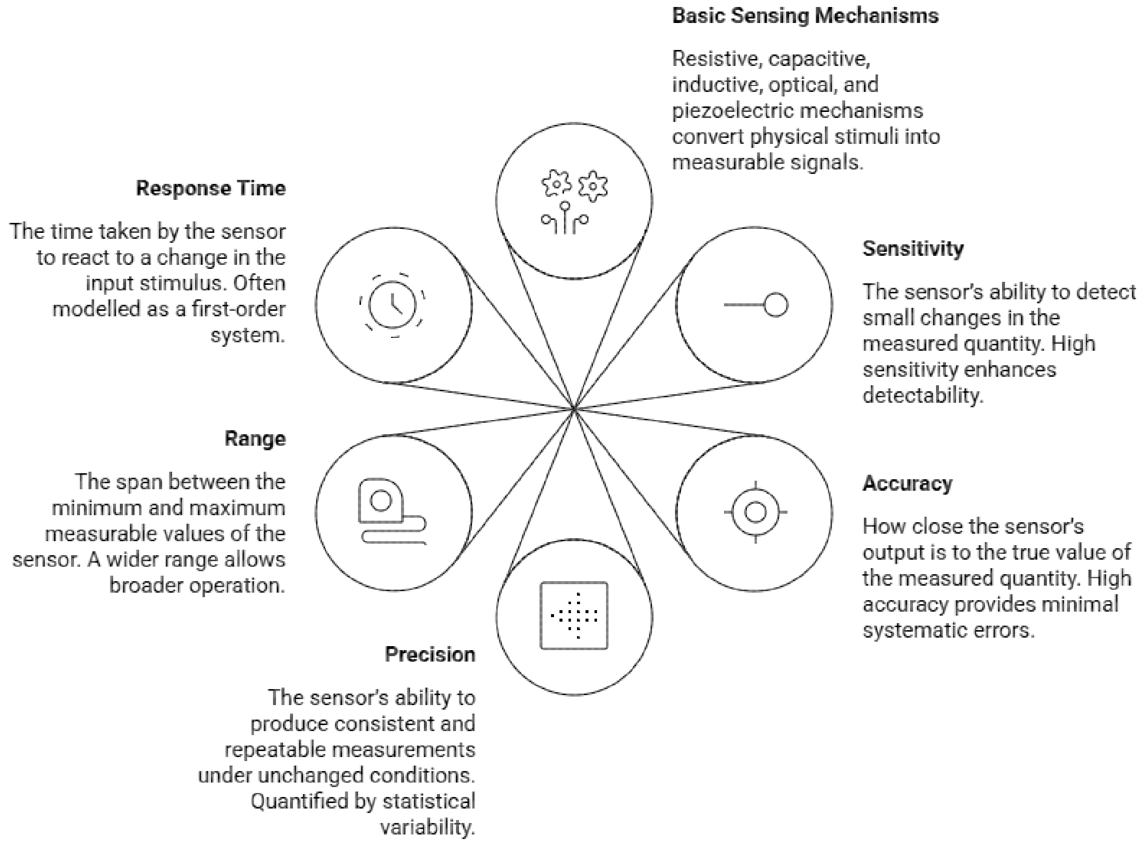

Figure 3: Sensor characteristics

Sensors with high accuracy provide measurements with minimal systematic errors

Precision describes the sensor's ability to produce consistent and repeatable measurements under unchanged conditions. It is quantified by the statistical variability, often the standard deviation of repeated measurements:

Range defines the span between the minimum and maximum measurable values of the sensor. A wider range allows the sensor to operate effectively over a broader spectrum of input values.

Response Time is the time taken by the sensor to react to a change in the input stimulus and reach a specified percentage of the final output value. It is often modelled as a first-order system. Together, these performance characteristics determine the sensor's reliability, suitability, and efficiency in various transformative science and technology applications [3].

Classification and Types of Sensors

Active and Passive Sensors

Active and passive sensors represent two fundamental categories in the classification of sensors based on their mode of operation. Active sensors require an external energy source to emit signals or stimuli, which interact with the target environment or object, and the sensor then detects the reflected or altered signals. Examples include RADAR and LIDAR systems, which emit electromagnetic waves and measure their reflection to determine distance or speed. In contrast, passive sensors do not emit any energy but instead detect natural energy or signals originating from the environment, such as thermal radiation or ambient light. Common passive sensors include photodiodes and thermocouples, which measure light intensity or temperature without influencing the measured phenomenon [3]. This distinction is crucial in transformative science and technology, as active sensors often enable more controlled and precise measurements in dynamic or complex environments, while passive sensors offer simplicity, lower power consumption, and minimal interference, supporting a wide range of applications from environmental monitoring to healthcare diagnostics.

Analog and Digital Sensors

Active and passive sensors can be understood within the broader classification of analog and digital sensors based on their signal processing and output characteristics [3]. Active sensors, which emit energy to interact with the environment and detect the reflected or altered signals, often generate analog outputs that represent continuous variations in the measured parameter, such as voltage or current changes in radar or lidar systems. These analog signals can then be converted into digital form for further processing and analysis. Passive sensors, by contrast, detect natural energy without emitting signals, typically producing analog outputs corresponding to physical quantities like light intensity or temperature, as seen in photodiodes and thermocouples [4]. Many passive sensors are paired with analog-to-digital converters to enable digital signal processing, enhancing accuracy and integration with modern digital systems. This interplay between active/passive operation and analog/digital signal handling is vital in transformative science and technology, where precise measurement and efficient data processing drive innovations across environmental sensing, healthcare, and industrial automation.

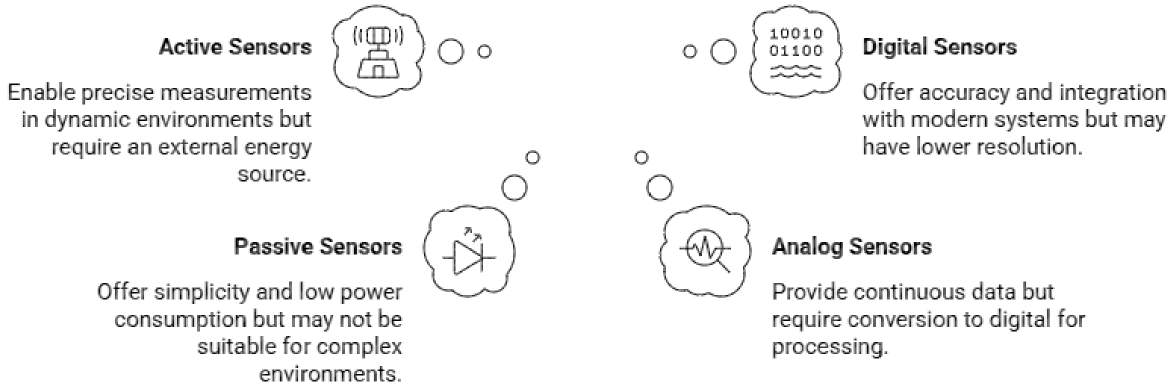

Figure 4: Sensors and their applications

Common Sensors: Temperature, Pressure, Light, Motion, Proximity, and Gas Sensors

Common sensors such as temperature, pressure, light, motion, proximity, and gas sensors represent essential categories within the broader classification of sensing devices, each designed to detect specific physical or chemical stimuli. Temperature sensors measure thermal variations using mechanisms like resistive or thermoelectric effects, enabling applications from environmental monitoring to healthcare. Pressure sensors detect force per unit area, often utilizing piezoelectric or capacitive principles, critical in industrial processes and automotive systems. Light sensors, including photodiodes and phototransistors, respond to ambient or directed light intensity, supporting applications in imaging, display technologies, and environmental sensing. Motion sensors detect movement or acceleration through mechanisms such as piezoelectric or inertial sensing, widely used in security systems and consumer electronics [4]. Proximity sensors identify the presence or absence of objects within a certain range, commonly employing capacitive or inductive methods, essential in automation and robotics. Gas sensors detect specific chemical compounds or concentrations by translating chemical interactions into electrical signals, playing a vital role in environmental safety and industrial monitoring. Together, these common sensors form the foundational toolkit for transformative science and technology, enabling precise measurement, control, and automation across diverse emerging domains.

Signal Conditioning and Data Acquisition

Need For Signal Conditioning

The output produced by most sensors is not immediately suitable for processing, storage, or transmission because it is often weak, noisy, nonlinear, or affected by environmental factors. Signal conditioning is the process of modifying and improving these raw sensor signals so that they can be accurately interpreted by electronic systems. It enhances signal quality by increasing amplitude, reducing unwanted noise, compensating for sensor nonlinearities, isolating sensitive circuits, and matching signal levels with the requirements of data acquisition systems [3]. Effective signal conditioning improves measurement accuracy, reliability, and stability, particularly in industrial automation, biomedical instrumentation, environmental monitoring, aerospace, and Internet of Things (IoT) applications. As modern sensing technologies continue to evolve, signal conditioning has become an indispensable stage that ensures sensor outputs are transformed into meaningful and reliable information for analysis and decision-making.

Amplification, Filtering, and Analog-To-Digital Conversion

Signal conditioning typically involves three fundamental processes: amplification, filtering, and analog-to-digital conversion (ADC). Amplification increases the magnitude of low-level signals generated by sensors such as thermocouples, strain gauges, and photodiodes without significantly altering their characteristics [5]. This enables accurate measurement and minimizes the influence of electrical interference. Filtering removes unwanted frequency components and electrical noise that may arise from electromagnetic interference, power-line disturbances, or environmental sources. Depending on the application, low-pass, high-pass, band-pass, or notch filters are employed to preserve the desired signal while suppressing unwanted components. Once the signal has been conditioned, it undergoes analog-to-digital conversion, where the continuous analog signal is sampled and converted into a digital representation. The quality of this conversion depends on parameters such as sampling rate and resolution, which determine how faithfully the digital data represents the original analog signal. The resulting digital information can then be processed by microcontrollers, digital signal processors, computers, or cloud-based analytical systems, enabling real-time monitoring, automation, and intelligent decision-making [6].

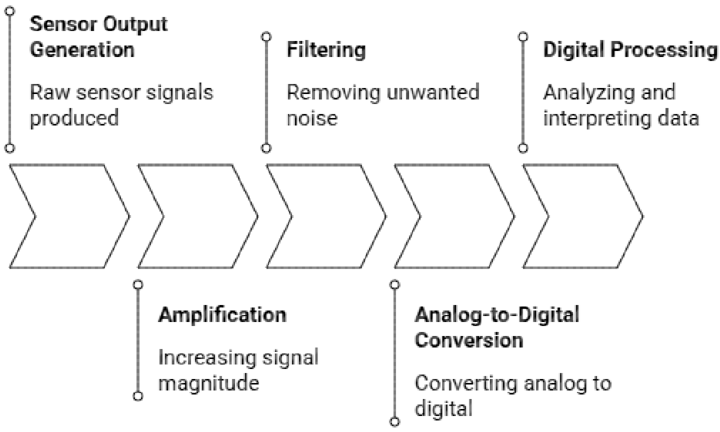

Figure 5: Signal conditioning and data acquisition process

Basic Measurement System

A basic measurement system is an integrated arrangement of components that acquires, processes, and presents information about a physical quantity. The system begins with the measurand, the physical parameter to be measured, such as temperature, pressure, displacement, or light intensity. A sensor or transducer detects the measurand and converts it into a corresponding electrical signal. This signal is then passed through a signal conditioning unit, where it is amplified, filtered, linearized, or isolated to improve its quality and compatibility with subsequent electronic circuits. The conditioned signal is forwarded to a data acquisition system (DAQ), which performs analog-to-digital conversion and transfers the digital data to a processing unit, such as a microcontroller or computer. The processed information is finally displayed, recorded, transmitted, or used to control other devices through feedback mechanisms [5]. In advanced measurement systems, wireless communication, cloud computing, artificial intelligence, and edge computing further enhance data analysis, predictive maintenance, and autonomous operation. This systematic flow—from sensing to signal conditioning, data acquisition, processing, and output—forms the foundation of modern instrumentation systems used in scientific research, industrial automation, healthcare, transportation, and smart infrastructure.

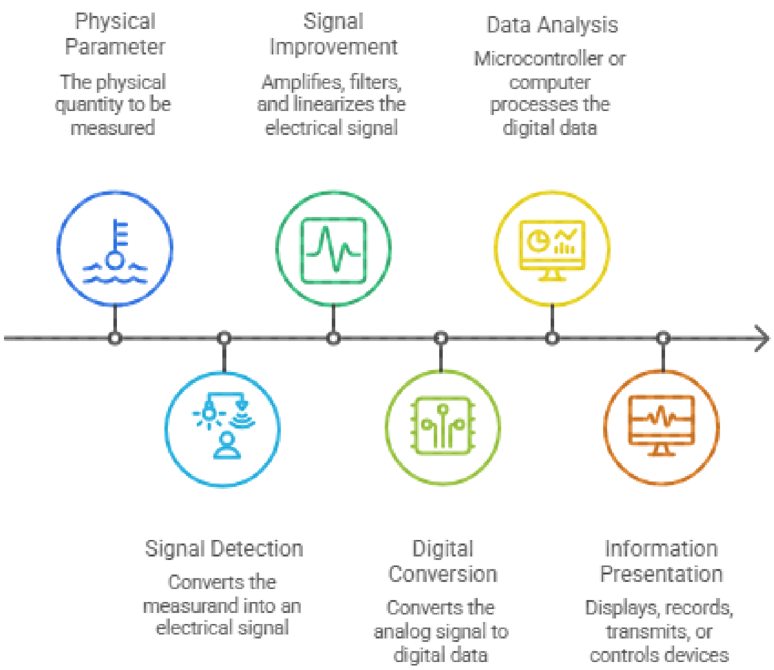

Figure 6: Basic measurement system workflow

Smart Sensors and Intelligent Detection Systems

Features of Smart Sensors

Smart sensors integrate sensing elements with embedded microprocessors or digital signal processors, enabling on-site data processing, self-calibration, diagnostics, and adaptive responses. Unlike conventional sensors, they offer enhanced accuracy, reliability, and functionality by minimizing external system complexity and reducing power consumption. Smart sensors support real-time data communication and seamless integration into networks, facilitating advanced automation and the Internet of Things (IoT) [4]. These features empower intelligent, interconnected devices to perform sophisticated monitoring, control, and predictive functions across diverse transformative science and technology applications.

Microcontroller-Based Sensing

Microcontroller-based sensing involves the use of microcontrollers to interface directly with sensor outputs, enabling real-time data acquisition, processing, and control within a compact system. The microcontroller manages signal conditioning tasks such as amplification and filtering, digitizes analog signals via integrated analog-to-digital converters, and executes embedded algorithms for calibration and error correction. This approach reduces system size and cost while enhancing flexibility and responsiveness. In transformative technologies, microcontroller-based sensing forms the core of smart sensor systems, supporting autonomous operation and seamless communication with larger digital infrastructures.

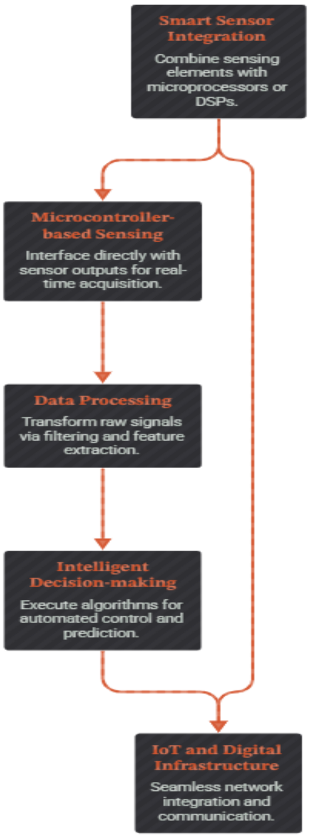

Figure 7: Smart sensors and intelligent detaection system architecture

Data Processing and Intelligent Decision-Making

Data processing in intelligent detection systems encompasses the transformation of raw sensor signals into meaningful information through filtering, feature extraction, and pattern recognition. Embedded processors or connected computing units analyze this data to identify trends, anomalies, or specific conditions, enabling automated decision-making without human intervention. Intelligent algorithms, including machine learning and adaptive control, empower these systems to optimize performance, predict failures, and adapt to changing environments [6]. This capability is critical in transformative science and technology, where timely, accurate decisions drive enhanced automation, safety, and efficiency in complex applications.

IoT-Based Sensor Networks

Concept of IoT

The Internet of Things (IoT) refers to a network of interconnected devices embedded with sensors, software, and communication capabilities that enable them to collect, exchange, and act on data autonomously. In IoT-based sensor networks, devices communicate in real-time, facilitating seamless integration and cooperation across diverse applications [7]. This connectivity transforms traditional sensing systems into intelligent ecosystems capable of continuous monitoring, adaptive control, and predictive analytics. The IoT paradigm underpins transformative science and technology by enabling scalable, distributed sensing infrastructures that support advanced automation, resource optimization, and enhanced decision-making processes.

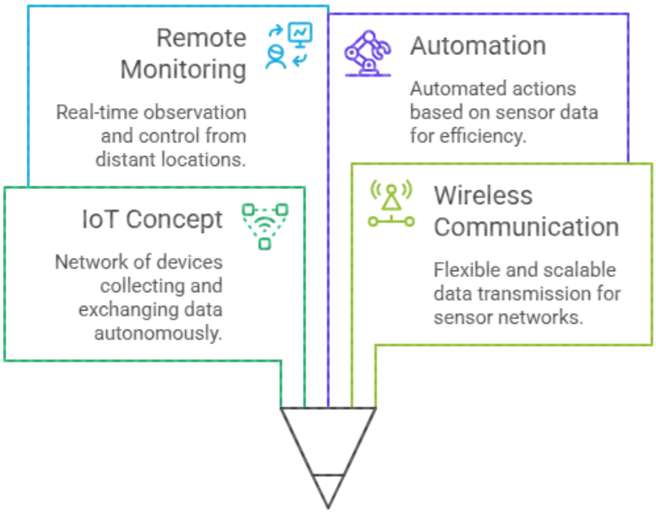

Figure 8: Future of sensing

Wireless Communication in Sensing Systems

Wireless communication plays a pivotal role in IoT-based sensor networks by enabling flexible, scalable, and cost-effective data transmission between distributed sensors and central processing units. Technologies such as Wi-Fi, Bluetooth, Zigbee, and cellular networks facilitate reliable, low-power, and real-time connectivity essential for sensor data acquisition and control [7]. Wireless links eliminate the constraints of wired connections, allowing sensor deployment in remote, inaccessible, or dynamic environments. This capability enhances system adaptability and integration into broader digital infrastructures, driving innovations in environmental monitoring, industrial automation, and smart city applications within transformative science and technology.

Remote Monitoring and Automation

Remote monitoring and automation leverage IoT-based sensor networks to observe and control systems from distant locations without direct human intervention. Sensor data transmitted via wireless communication channels enable continuous real-time tracking of environmental, mechanical, or physiological parameters. Automated algorithms process this information to trigger responsive actions, optimize system performance, and predict maintenance needs [7]. This approach enhances operational efficiency, safety, and reliability across diverse domains such as healthcare, manufacturing, and infrastructure management. By enabling timely, data-driven decision-making, remote monitoring and automation are foundational to the next generation of intelligent, interconnected systems in transformative science and technology.

Applications of Smart Detection Systems

Industrial Automation

Smart detection systems play a pivotal role in industrial automation by enabling precise monitoring, control, and optimization of manufacturing processes. These systems integrate advanced sensors with real-time data processing and communication capabilities, facilitating automated decision-making and reducing human intervention [6]. By continuously tracking parameters such as temperature, pressure, vibration, and flow, smart sensors help maintain product quality, enhance operational efficiency, and predict equipment failures before they occur. Their ability to seamlessly connect with broader digital infrastructures supports the implementation of Industry 4.0 principles, driving transformative improvements in productivity, safety, and resource management across diverse industrial sectors.

Healthcare and Wearable Devices

In healthcare, smart detection systems underpin the development of wearable devices that continuously monitor physiological parameters such as heart rate, blood oxygen levels, and physical activity. These devices employ embedded sensors combined with intelligent data processing to provide real-time health insights, early detection of anomalies, and personalized feedback [8]. The integration of wireless communication enables remote patient monitoring, enhancing accessibility and reducing the need for frequent clinical visits. Wearable smart sensors contribute significantly to preventive medicine, chronic disease management, and rehabilitation, transforming healthcare delivery toward more proactive, data-driven, and patient-centered models.

Environmental Monitoring

Smart detection systems are essential in environmental monitoring applications, where they provide accurate, real-time data on air and water quality, temperature, humidity, and pollutant levels. These systems leverage networks of distributed sensors capable of autonomous operation and wireless communication, enabling large-scale, continuous surveillance of ecosystems and urban environments. Intelligent data analysis facilitates early warning of hazardous conditions, supports regulatory compliance, and informs sustainable resource management [8]. By integrating these capabilities, smart detection systems empower environmental scientists and policymakers to address challenges such as climate change, pollution control, and disaster mitigation with greater precision and responsiveness.

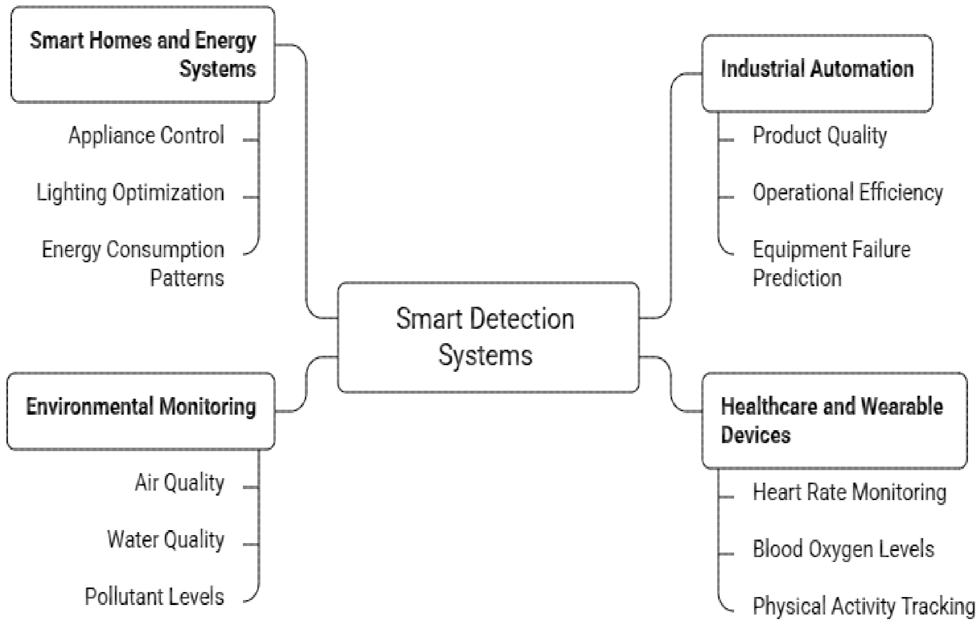

Figure 9: Applications of smart detection systems

Smart Homes and Smart Energy Systems

Smart detection systems form the backbone of smart homes and energy management solutions by enabling automated control and optimization of appliances, lighting, heating, ventilation, and air conditioning systems. Embedded sensors detect occupancy, environmental conditions, and energy consumption patterns, feeding data into intelligent algorithms that adjust system operations for comfort, efficiency, and cost savings. Integration with IoT networks allows remote monitoring and management, enhancing user convenience and supporting demand-response strategies in smart grids. These systems contribute to reducing energy waste, lowering carbon footprints, and advancing sustainable living environments aligned with transformative science and technology goals.

Future Trends and Challenges

MEMS and Nanosensors

Microelectromechanical systems (MEMS) and nanosensors represent a cutting-edge evolution in sensor technology, leveraging miniaturization to achieve highly sensitive, compact, and energy-efficient devices. MEMS integrate mechanical elements, sensors, actuators, and electronics on a single silicon chip, enabling precise detection of physical parameters such as pressure, acceleration, and chemical composition at microscale dimensions. Nanosensors operate at the molecular or atomic scale, offering unprecedented sensitivity and specificity by exploiting nanomaterials' unique electrical, optical, or mechanical properties [9]. These technologies facilitate real-time, high-resolution monitoring in diverse transformative science and technology fields, including biomedical diagnostics, environmental sensing, and industrial process control. Their continued development promises enhanced integration with smart systems, enabling more sophisticated, distributed sensing networks.

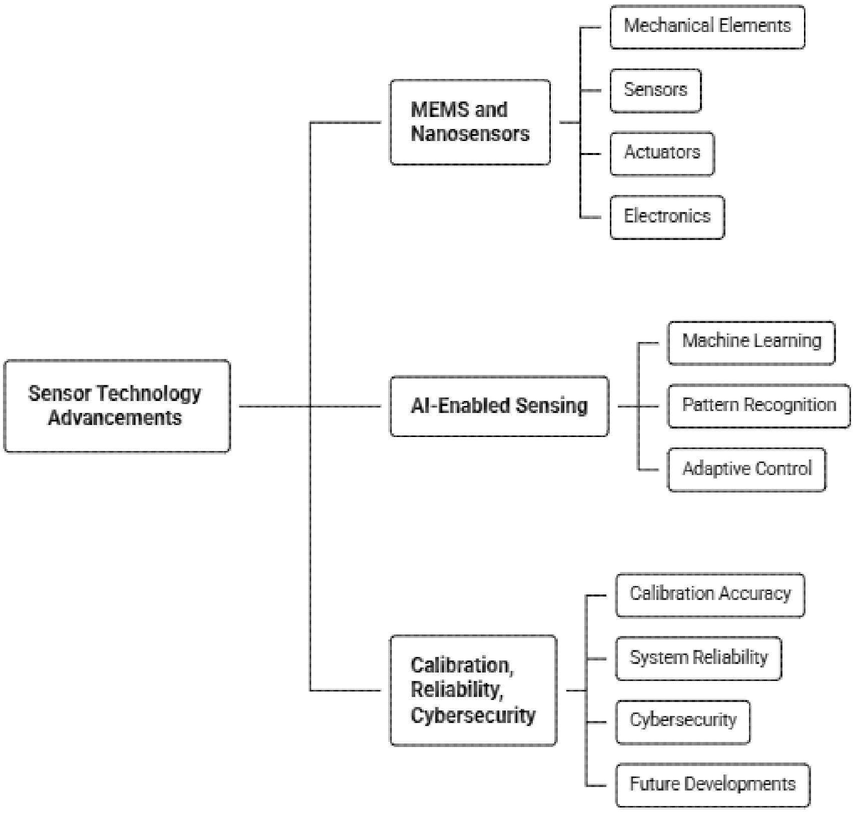

Figure 10: Advancements in Sensor Technology

AI-Enabled Sensing

AI-enabled sensing integrates artificial intelligence algorithms with sensor data acquisition to enhance the interpretation, accuracy, and utility of sensed information. By employing machine learning, pattern recognition, and adaptive control techniques, AI systems can extract complex features from raw sensor data, identify anomalies, and predict system behaviors with minimal human intervention [10]. This fusion of AI and sensing technology enables intelligent decision-making, real-time adaptation to dynamic environments, and improved fault detection, thereby elevating the performance of smart detection systems. In transformative science and technology, AI-enabled sensing drives innovations across sectors such as autonomous vehicles, precision agriculture, and healthcare, where data-driven insights are critical for optimizing operations and outcomes.

Calibration, Reliability, Cybersecurity, and Future Developments

Ensuring calibration accuracy and system reliability remains a fundamental challenge as sensor networks grow more complex and pervasive. Regular calibration corrects sensor drift and environmental influences, maintaining measurement precision essential for dependable operation. Reliability encompasses robustness to physical stress, environmental variability, and long-term stability, critical for continuous monitoring applications. As sensor systems increasingly connect to digital networks, cybersecurity emerges as a vital concern to protect data integrity, privacy, and system availability from malicious attacks [9]. Future developments focus on integrating self-calibration capabilities, enhancing fault tolerance, and embedding advanced encryption and authentication protocols. Additionally, emerging trends include leveraging edge computing and block chain technologies to bolster security and data trustworthiness, positioning smart sensing systems at the forefront of resilient, secure, and autonomous infrastructures in transformative science and technology.

References

1. Sharma, A., Sharma, S., & Gupta, D. (2021). A review of sensors and their application in Internet of Things (IoT). *International Journal of Computer Applications, 174*(24), 27–34.
2. Brida, P., Krejcar, O., Selamat, A., & Kertesz, A. (2021). Smart sensor technologies for IoT. *Sensors, 21*(17), 5890. https://doi.org/10.3390/s21175890
3. Leelaarporn, P., et al. (2021). Sensor-driven achieving of smart living: A review. *IEEE Sensors Journal, 21*(9), 10369–10391. https://doi.org/10.1109/JSEN.2021.3055614
4. Vazarde, G., & Narkhede, S. (2021). Survey on smart sensors. *Journal of Science & Technology, 6*(Special Issue 1), 340–344.
5. *Sensors as the basis for digitalization: New approaches in instrumentation, IoT concepts, and 5G.* (2021). *Internet of Things, 15*, 100406. https://doi.org/10.1016/j.iot.2021.100406
6. Costa, F., Genovesi, S., Borgese, M., Michel, A., Dicandia, F. A., & Manara, G. (2021). A review of RFID sensors, the new frontier of Internet of Things. *Sensors, 21*(9), 3138. https://doi.org/10.3390/s21093138
7. Mukhopadhyay, S. C., Tyagi, S. K. S., Suryadevara, N. K., Piuri, V., Scotti, F., & Zeadally, S. (2021). Artificial intelligence-based sensors for next-generation IoT applications: A review. *IEEE Sensors Journal, 21*(22), 24920–24932. https://doi.org/10.1109/JSEN.2021.3119228
8. Pech, M., Vrchota, J., & Bednář, J. (2021). Predictive maintenance and intelligent sensors in smart factory: Review. *Sensors, 21*(4), 1470. https://doi.org/10.3390/s21041470
9. Gazis, A., Papadongonas, I., Andriopoulos, A., Zioudas, C., & Vavouras, T. (2025). A comprehensive review of sensor technologies, instrumentation, and signal processing solutions for low-power Internet of Things systems with mini-computing devices.
10. Nguyen, D. C., Ding, M., Pathirana, P. N., Seneviratne, A., Li, J., & Poor, H. V. (2021). Federated learning for Internet of Things: A comprehensive survey. *IEEE Communications Surveys & Tutorials, 23*(3), 1622–1658. https://doi.org/10.1109/COMST.2021.3075439

STATE-SPACE ANALYSIS OF NONLINEAR SHIP ROLL MOTION SUBJECTED TO PERIODIC WAVE EXCITATION

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Abstract

This study investigates the nonlinear roll motion of a ship subjected to periodic external wave excitation using a nonlinear second-order differential equation. The governing equation incorporates linear damping, quadratic nonlinear damping, nonlinear restoring stiffness, and harmonic forcing to accurately represent the complex roll dynamics experienced in marine environments. The nonlinear restoring term and velocity-dependent damping capture the inherent nonlinear behavior of ship roll motion, while the sinusoidal excitation models wave-induced forcing. This mathematical formulation provides a foundation for investigating transient and steady-state responses, phase trajectories, stability characteristics, and nonlinear phenomena such as resonance and bifurcation. The model serves as an effective benchmark for evaluating numerical integration

Keywords: Nonlinear Roll Motion, Ship Dynamics, Nonlinear Ordinary Differential Equations, Harmonic Wave Excitation, State-Space Formulation, Akbari–Ganji Method (AGM).

Introduction

Ship roll motion is one of the most critical dynamic responses affecting the safety, stability, and operational performance of marine vessels. Excessive roll motion caused by environmental disturbances such as wind, waves, and currents can reduce passenger comfort, impair cargo safety, and, under severe conditions, lead to capsizing. Consequently, the accurate mathematical modeling and analysis of ship roll dynamics have attracted significant attention in naval architecture and ocean engineering.

The roll motion of a ship exhibits inherently nonlinear characteristics due to the combined effects of nonlinear restoring moments, viscous damping, and external wave excitation. While linear models are suitable for small roll angles, they fail to accurately describe the complex behavior observed under moderate and large-amplitude motions. Nonlinear roll models incorporating cubic restoring stiffness and quadratic damping provide a more realistic representation of ship dynamics and are capable of capturing important phenomena such as resonance, bifurcation, and chaotic motion [1-5]

The nonlinear roll motion equation is commonly represented as a Duffing-type oscillator with damping and periodic forcing. The inclusion of both linear and nonlinear damping terms accounts for viscous and hydrodynamic energy dissipation, whereas the cubic restoring term models the nonlinear stability characteristics of the vessel. The harmonic excitation represents wave-induced external forces acting on the ship. Such models have been extensively employed to investigate the dynamic response and stability of marine structures under realistic sea conditions [6-8]

To facilitate numerical analysis, the second-order nonlinear differential equation is transformed into an equivalent system of first-order ordinary differential equations using state variables representing the roll angle and roll angular velocity. This state-space formulation enables the application of advanced numerical integration techniques for evaluating transient responses, phase portraits, stability properties, and nonlinear dynamic behavior. The present study considers a nonlinear roll motion model with linear damping, quadratic nonlinear damping, cubic restoring stiffness, and harmonic wave excitation, providing a suitable benchmark for the analysis of nonlinear ship dynamics.

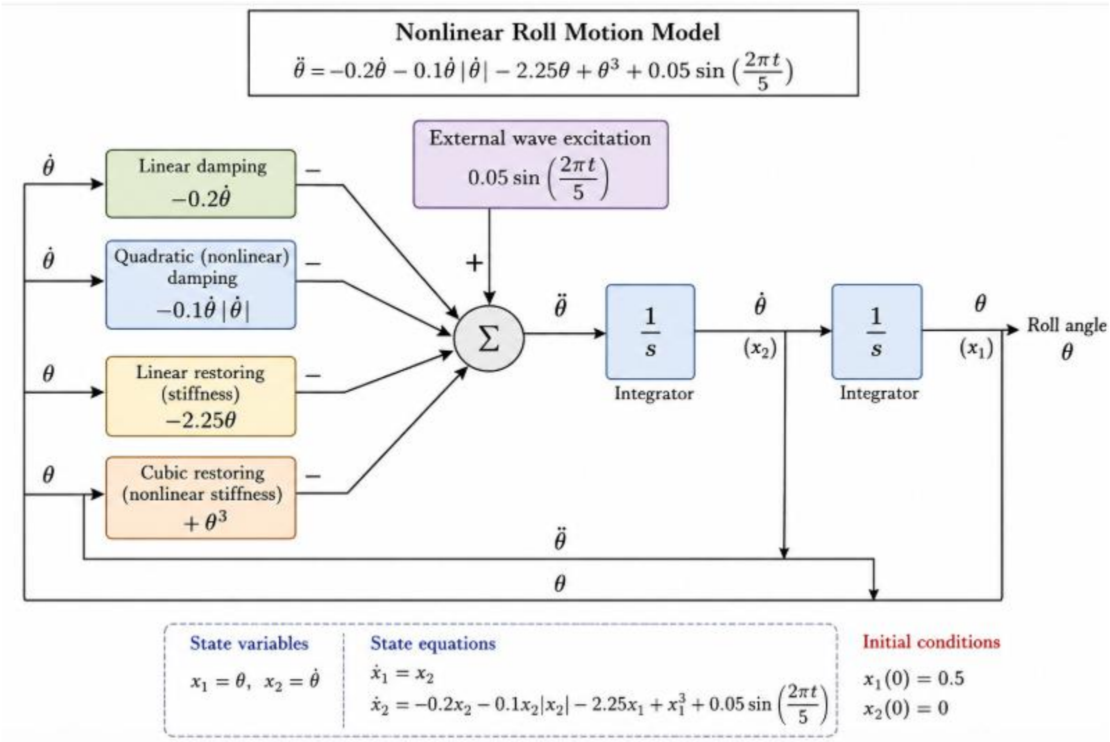

Figure 1: schematic diagram for nonlinear roll motion of ship

2. Theory

The Nonlinear roll motion equation

Define

$x_1 = \theta, x_2 = \dot{\theta}, \dot{x}_1 = x_2$, (1)

The system becomes

$\dot{x}_2 = -0.2x_2 - 0.1x_2 \mid x_2 \mid -2.25x_1 + x_1^3 + 0.05\sin\left(\frac{2\pi t}{5}\right)$, (2)

subject to the initial conditions

$x_1(0) = 0.5, x_2(0) = 0.$ (3)

where Two integrators converting angular acceleration → angular velocity → roll angle. Linear damping: $-0.2\dot{\theta}$, Quadratic nonlinear damping: $-0.1\dot{\theta} \mid \dot{\theta} \mid$, Linear restoring stiffness: -2.25θ, Nonlinear cubic restoring stiffness: $+\theta^3$, Periodic wave excitation: $0.05\sin(2\pi t/5)$.

3. Result and Discussion

The Akbari–Ganji Method (AGM) is a semi-analytical approach for solving nonlinear differential equations approximately. In this method, the solution is assumed in the form of a polynomial trial function with unknown coefficients. These coefficients are evaluated by substituting the assumed function into the governing nonlinear differential equation and satisfying the prescribed initial or boundary conditions together with the residual equations. Solving the resulting system of algebraic equations determines the unknown coefficients, leading to an accurate analytical approximation of the nonlinear solution with minimal computational effort.the third-order Akbari–Ganji Method (AGM) trial solution is typically assumed as

$\theta(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3$ (4)

Applying the initial conditions,

$a_0 = 0.5, a_1 = 0$ (5)

Hence, the third-order AGM trial solution becomes

$\theta(t) = 0.5 + a_2 t^2 + a_3 t^3$ (6)

where $a_2 = -0.5, a_3 = 0.03914.$ (7)

Applying the third-order Akbari–Ganji Method (AGM) to the nonlinear roll motion equation and satisfying the prescribed initial conditions yields the approximate displacement solution

$\theta(t) = 0.5 - 0.5\,t^2 + 0.03914t^3$ (8)

The corresponding velocity and acceleration are obtained by differentiating the displacement with respect to time as

$\dot{\theta}(t) = \frac{d\theta}{dt} = -\,t + 0.11742\,t^2$ (9)

Figure 2 illustrates the velocity response of the damaged ship over a simulation period of 10 s. The response exhibits damped oscillatory behavior, with the amplitude gradually decreasing over time, indicating the presence of energy dissipation within the system. Initially, the roll velocity attains peak values of approximately ±0.2 cm/s, and the oscillations progressively diminish as the simulation advances. This reduction in amplitude is primarily due to the combined effects of linear and nonlinear (quadratic) damping, which continuously dissipate the system's kinetic energy during motion. Although the ship is subjected to harmonic wave excitation, the damping mechanisms effectively suppress excessive oscillations and enhance the dynamic stability of the system.

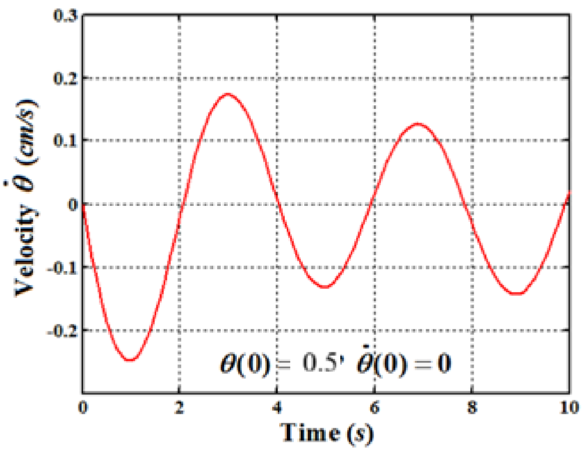

Figure 2: Time History of Roll Velocity of the Nonlinear Ship Roll Motion Using the eq. (9)

The obtained velocity response demonstrates the capability of the nonlinear roll motion model to accurately describe the damped dynamics of the damaged ship, while the AGM solution provides a reliable approximation of the transient oscillatory behavior throughout the simulation interval.The acceleration is obtained by

$$\ddot{\theta}(t) = \frac{d^2\theta}{dt^2} = -1 + 0.23484\,t. \quad (10)$$

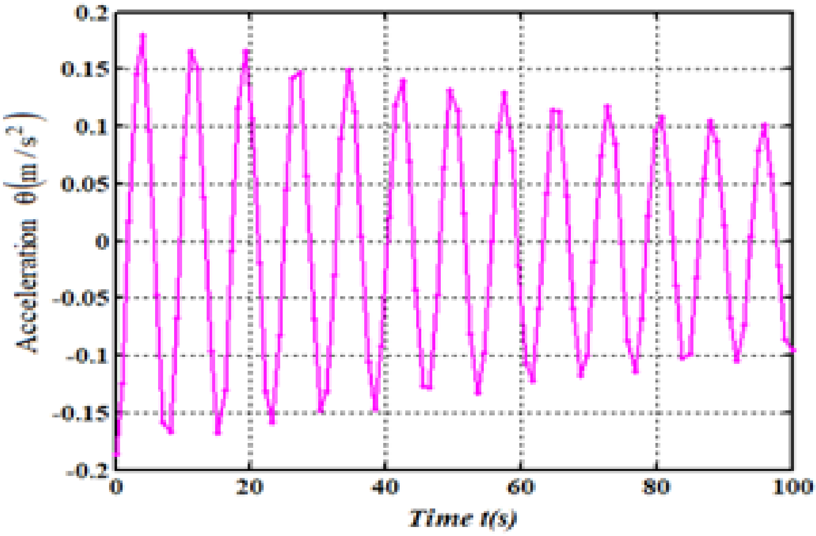

Figure 3: Time History of Roll Acceleration of the Nonlinear Ship Roll Motion using the eq. (10)

Figure 3 illustrates the acceleration response of the damaged ship over a simulation period of 100 s. The response exhibits damped oscillatory behavior with nearly periodic fluctuations throughout the simulation. At the beginning of the motion, the peak acceleration reaches approximately ±0.17 m/s², and its amplitude gradually decreases to about ±0.10 m/s² as time progresses. This attenuation is primarily caused by the combined effects of linear and nonlinear (quadratic) damping, which continuously dissipate the system's energy. Despite the presence of harmonic wave excitation, the damping mechanisms effectively suppress excessive oscillations and maintain the dynamic stability of the ship. Furthermore, the absence of abrupt changes or divergent behavior confirms the stable nature of the nonlinear roll motion. The obtained acceleration response demonstrates that the AGM solution accurately captures the transient dynamic characteristics of the damaged ship throughout the simulation period.

Conclusion

The nonlinear roll motion equation provides an effective mathematical representation of the complex rolling behavior of a ship subjected to periodic wave excitation. By incorporating linear damping, quadratic nonlinear damping, linear restoring stiffness, nonlinear cubic restoring stiffness, and harmonic external forcing, the model accurately captures the essential physical mechanisms governing ship roll dynamics. Transforming the second-order differential equation into a system of first-order state-space equations simplifies the numerical implementation and enables efficient analysis of the system's dynamic response. The nonlinear terms allow the model to represent large-amplitude roll motions that cannot be adequately described by linear models, making it suitable for investigating stability, resonance, transient response, and other nonlinear phenomena. Furthermore, the adopted formulation serves as a reliable benchmark for evaluating numerical integration techniques and advanced computational methods used in marine engineering. Overall, the nonlinear roll motion model provides valuable insight into ship stability and dynamic performance, contributing to the development of safer and more efficient marine vessels operating under realistic sea conditions.

References

1. Nayfeh, A. H., & Mook, D. T. (1979). *Nonlinear oscillations*. John Wiley & Sons.
2. Thompson, J. M. T., & Stewart, H. B. (2002). *Nonlinear dynamics and chaos* (2nd ed.). John Wiley & Sons.
3. Virgin, L. N. (2000). *Introduction to experimental nonlinear dynamics*. Cambridge University Press.
4. Falzarano, J. M., & Shaw, S. W. (1992). Application of global analysis methods for predicting vessel capsize. *Journal of Ship Research, 36*(2), 133–149.
5. Fossen, T. I. (2021). *Handbook of marine craft hydrodynamics and motion control* (2nd ed.). John Wiley & Sons. https://doi.org/10.1002/9781119575054
6. Roberts, J. B. (1982). A stochastic theory for nonlinear ship rolling in random beam seas. *Journal of Ship Research, 26*(4), 229–238.
7. Ibrahim, R. A. (2005). *Liquid sloshing dynamics: Theory and applications*. Cambridge University Press. https://doi.org/10.1017/CBO9780511536656
8. Francescutto, A. (1995). Theoretical and experimental study of ship rolling in nonlinear waves. *Marine Technology, 32*(2), 117–128.

PORTABLE REFRIGERATION SYSTEM: ECO-FRIENDLY AND ENERGY-SAVING APPROACH

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Abstract

Conventional refrigeration system often experiences challenges like high cost, limited reliability, poor energy efficiency, and lack of environmental sustainability. To mitigate these issues, portable refrigeration systems are designed with innovative, sustainable and energy efficient features like wood wool insulation, water-circulated pipe grid for enhanced heat transfer, duct fans to create pressure difference, and heat sinks for heat exchange. These elements create an efficient and environment friendly system. The portable refrigerator is sustainable, energy-efficient, and ideal for off-grid applications where mobility and convenience are to be prioritised. This includes small portable applications like road journeys, outdoor expeditions, excursions in remote areas, medical conveyance kits, as well as field visits and studies in isolated areas. The system's reliability, performance and the energy saving features are exceptional. By addressing the key limitations of conventional refrigeration systems, the multifunctional portable refrigeration system paves the way for eco-friendly cooling solution that offers improved cooling, reduced energy drains and compact and lightweight design while maximizing storage capacity, ensuring portability without compromising usability.

Keywords: Eco-Friendly, Energy Saving, Heat Sink, Peltier, Portable, Refrigerator.

1. Introduction

Refrigeration is a process of reducing the temperature of system or space by removal of heat. It is associated with domestic or commercial cooling of agricultural commodities, food products and health care products with the help of mechanised system. Variety of refrigeration systems presented to the market, as vapour compression, absorption along with emerging techniques like thermoelectric, magnetic, steam jet systems are utilized to fulfil the cooling requirements at domestic and commercial levels. Conventional vapour compression refrigeration systems utilizing compressor and refrigerant is an energy consuming technique (Patil and Kulkarni, 2016). These systems are bulky and costly, hence not suitable for small portable applications like road journeys, outdoor expeditions, excursions in remote areas, medical conveyance kits, as well as field visits and studies.

Portable refrigerator is an appropriate solution for such kind of applications where mobility and convenience are to be prioritised and where conventional refrigeration systems are inadequate. Portable cooling systems are intended for widespread requirements including indoor, outdoor, and travelling ventures and emergency needs. These systems can maintain the suitable temperature in diverse climatical conditions to ensure the safety of food and temperature-sensitive items, regardless of any location. The portable cooling systems are convenient and versatile as they can operate on diversified power supplies such as batteries and vehicle DC power (Eslami Majd *et al.,* 2023). During outdoor events, portable refrigerators are the excellent choice to preserve the freshness of food and to maintain the coldness of beverage over extended timespan. Moreover, these systems offer a splendid option to healthcare professionals during transportation of vaccines, blood samples, and other sensitive medical materials ensuring their safety. Field researchers those who are working in remote conditions benefit themselves by using such portable refrigerators for preserving biological samples and other critical materials under extreme temperature conditions (Maity *et al.,* 2023). As the demand for portable cooling system increases, it becomes more important to develop more efficient system that are more user compatible and durable taking portability and efficiency into consideration. This chapter explores the designing of portable refrigeration system that addresses the key limitations of existing models, such as high energy consumption, less mobility and less cooling efficiency. The system uses heat sink and pipe grid cooling mechanism that are the convectional way of cooling used in olden days. The insulation like wood wool is also used to trap the heat and dissipate it throughout the entire system (Dhruw *et al.,* 2023).

The portable refrigeration system offers ecofriendly option as the use of refrigerant and compressor is eliminated that turned down the emission of harmful gases. The system can be upgraded in future research looking to the continuous advancements in portable refrigeration system involving use of light weight material, increase in storage space, integration of IoT device for distant operating and monitoring of portable refrigeration device. Additionally, the increasing adoption of renewable energy sources (solar and wind) will make these units more sustainable and accessible to a wider range of users. By addressing both environmental and practical challenges, portable refrigerator provides an option which is not only effective and reliable but also highly sustainable approach for reducing the carbon footprint. The features of refrigerators are demonstrated in Table 1.

Table 1: Diversity profile of refrigeration techniques

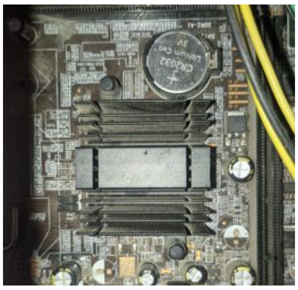
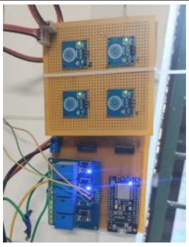
Facet	Features of existing refrigeration system
Type of Portable refrigeration	• Compressor based system: Compact and energy efficient using less power • Thermoelectric cooler: Low power but less efficient in extreme conditions • Absorption refrigeration: Use of eco-friendly refrigerants such as R290 (propane)

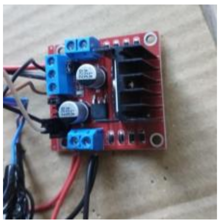
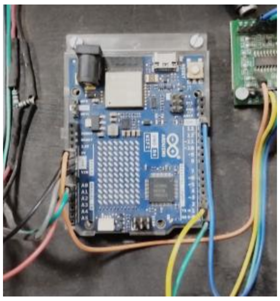
Performance in hot climates	• Cooling efficiency decreases by 20-40% in extreme climates (>40°C), especially for thermoelectric systems. • Advanced insulation materials like VIPs or PCMs improve thermal efficiency by reducing heat loss. • Compressor based units perform better in extreme temperatures, reaching lower internal temperatures than TECs. • Compressors are better suited for high-demand applications like medical transport.
Cooling Technology	• Compressor based cooling: Achieves temperatures as low as -18°C or below, offering superior cooling performance. • Thermoelectric cooling: Less effective in hot climates but lighter and quieter, suitable for moderate environments. • Cryogenic cooling: High-end models use this technology for efficient cooling, though it is costly and bulkier.
Durability and Portability	• Structural weaknesses: Portable refrigerators face damage during transport; rugged materials like hard plastics and aluminum alloys enhance durability. • Noise from compressors: Innovations like soundproof housing and anti-vibration tech reduce compressor noise. • Design Improvements: Shock absorbers, reinforced corners, and weatherproofing features boost durability.
Material and Insulation	• Insulation Technologies: Polyurethane foam is common, but vacuum insulation panels (VIPs) improve insulation without adding bulk. • Lightweight Materials: Advanced polymers and composites offer lightweight yet durable refrigeration units.

2. Conceptual Design and Material Required

The conceptual design of this portable refrigerator consists of various essential components such as wood wool, that is arranged in alternate layers to facilitate convective heat transfer. After the layer of wood wool, a system of pipe grid is arranged through which water is passed to remove excess heat, and it is used to partially cool the system. This layer is covered by sandwiching wood wool, which absorbs coldness from the pipe, and helps in enhancing the heat exchange process. The components used in this refrigeration system are two heat sinks, used specifically for effective heat dissipation, a set of duct fans at top and bottom to circulate cold air inside the insulating enclosure to maximise cooling efficiency. In-depth analysis was conducted for the selection of material on the basics of their properties. The electric components were selected on the basic of their specification such as drawn voltage, current consumption, power, and compatibility with other components. This allows thorough assessment for optimized functionality and energy efficiency in the final design, ensuring that all materials and electronics are suited for reliable, long-term operation in the intended application. Components used in the design of portable refrigeration system are showcased in Table 2.

Table 2: Component of portable refrigeration system

Material	Specification and usage	Picture
Wood wool	Wood wool sheets are lightweight, and it absorbs coldness from cooling pipes, enhancing the overall heat exchange process. It is often used as an insulation material in refrigeration systems to prevent heat exchange between the interior of the refrigeration unit and the external environmental (Caleb *et al.,* 2019).	
Heat sink	Heat sink is a passive heat transfer equipment that exchanges the heat produced by a source with a cooling medium (air or liquid coolant). 2 heat sinks (3.5 x 3.5 inches) are used in this refrigerator. Each heat sink being attached to hot and cold side of the device, results into specific temperature outcome. On each heat sink, a cooling fan is installed to help in diffusing the temperatures (Alghanima *et al.,* 2022).	
Duct Fans	Cooling fans are used on both sides of system, one for circulation of cold air and other to dispel hot air. With the help of fan, the hot side dissipate the hot air outside the refrigerator box and the cold side fan dissipate the cold air inside the box (Afshari *et al.,* 2022).	
Peltier module	It is thermoelastic module that become cold while the other side heats up, making them ideal for precision cooling in electronics, portable refrigerators and temperature control systems (Suman *et al.,* 2020).	

Relay module or MOSFETs	It is an electrically operated switch used to control high power devices by isolating the low power control circuit from high power load making is ideal for AC and DC. These are used to increase the efficiency of cooling systems by guiding and circulating the air flow (Asyiqin *et al.,* 2019).	
Microcontroller:	The Arduino UNO R3 is used in portable refrigeration to control temperature, manage power, and regulate the cooling system. By connecting to temperature sensor, the Arduino monitors internal temperature and controls Peltier modules through relay MOSFETs. It also adjusts the fan speed using PWM for efficient cooling, while optimizing power consumption to ensure energy efficiency in battery power system (Asyiqin *et al.,* 2019).	
Flat pipe grid	A water pipe grid cooling system circulates water through a network of pipes to absorb and transfer heat from various sources. The water flowing through the grid absorbs heat and is then cooled in a heat exchanger before being recirculated in a continuous loop (Ong, 2016; Ai *et al.,* 2024).	
Water pump	The brushless motor of pump ensures longer life with reduced maintenance, while its compact size and low power consumption make it suitable for battery-powered system. With a waterproof design and low noise level, this pump is perfect for liquid circulation in the systems that require reliability and energy efficiency, such as water cooling for electronics to create a continuous circulation of water in flat pipes (Ong, 2016) that are used in the internal walls of the cooling chamber.	

3. Design Criteria

beverages, medical and pharmaceutical uses, vaccines, and medicines that are temperature sensitive. It can also be used in emergency such as disaster relief and emergency services or it can be used in military operations. This refrigeration system can be used by outdoor activists and adventurers in camping, hiking to store drinks and food. It can be used for fishing to preserve fish or baits in outdoor conditions. This system can be used during travelling, road trips, boating and sailing to keep perishables fresh and in the services like catering and food delivery, personal and office use, scientific research, agriculture and many more. This portable refrigerator is DC operated and can also be used on batteries.

The cost to manufacture portable refrigeration system comprises the charges for material like wood wool, duct fans, heat sink, outer layer, pipe gride, pump etc. and, electronics (MOSFETs, Arduino UNO R3, Peltier module, etc.) including making charges.

4. Performance of Portable Refrigeration System

Table 3: Performance indicators of portable refrigeration system

Experimental parameter	Formula to determine
Mass of air	$m = \rho \cdot V$
Temperature difference	$\Delta T = T_a - T_i$
Energy required	$Q = m \cdot c_p \cdot \Delta T$
Power required to achieve cooling in 30 min	P_Required = Q/t
Coefficient of performance	$COP = T_{cold} / (T_{hot} - T_{cold})$

Temperature Consistency

The portable refrigerator maintains stable temperature (5±2°C) at desired level with the inclusion of water-cooled flat pipe grid system. The components used are capable of carrying out the heat transfer process efficiently that ensures steady and uniform cooling without fluctuations, making it suitable to store perishable items and temperature-sensitive products. The water-cooled flat pipe grid helps in maintaining temperature consistency, even in extreme environmental conditions. This feature ensures reliable cooling performance for applications such as medical transport, outdoor expeditions, and food storage. Unlike traditional models this refrigerator is more reliable in high temperature conditions and can also deliver efficient cooling.

Energy Efficiency

The low power requirement for cooling of air highlights the energy-saving feature of the portable refrigerator. The parts are theorized to reduce energy consumption significantly while allowing the refrigerator to operate efficiently on battery power making it ideal for various off-grid applications or scenarios where power sources are limited. The use of water-cooled flat pipe grid, wood wool and heat sink reduce the energy consumption significantly. As this refrigerator is battery operated it does not require any power-hungry electric system. The power consumption is very less compared to any other portable refrigerator as there is no use of compressor. When compared to traditional portable refrigerators, the proposed model outperforms in lower battery consumption. This design minimizes power drainage, which is a significant improvement for battery-dependent users.

COP

The coefficient of performance (COP) is a performance measure of refrigeration system. The portable refrigerator addresses the major limitations in existing portable refrigerators by combining energy efficiency, enhanced cooling, and reducing time to cool from atmospheric temperature to 5 degrees Celsius. This provides a strong foundation for developing an energy-conserving and sustainable portable refrigeration system.

Conclusion

The portable refrigerator with energy-efficient system offers an innovative solution to overcome the limitations of traditional portable refrigerators. By focusing on energy efficiency, durability, and effective cooling, it demonstrates significant potential in addressing the needs of users in diverse environments. This system justifies energy efficiency through heat sink, enhanced cooling performance through water-cooled flat pipe grid, and improved portability and durability through use of light weight material like wood wool and heat sink based on lower energy and power requirement with improved COP.

References

1. Patil, R., & Kulkarni, V. S. (2016). Design and experimental analysis of portable refrigerator system. *International Journal of Advance Research and Innovative Ideas in Education (IJARIIE), 2*(3).
2. Eslami Majd, A., Tchuenbou-Magaia, F., Meless, A. M., Adebayo, D. S., & Ekere, N. N. (2023). A review on cooling systems for portable energy storage units. *Energies, 16*(18), 6525. https://doi.org/10.3390/en16186525
3. Maity, S., Aakriti, J., Manandhar, S., Anchan, S. B., Bhat, A., Shetty, M. U., & Nayak, Y. (2023). Emvolio—A battery-operated portable refrigerator preserves biochemical and haematological integrity of biological samples in preclinical studies. *F1000Research, 1*, 223. https://doi.org/10.12688/f1000research.109134.3
4. Dhruw, K., Sahu, H., Kumar, M., Tripathi, A., & Sahu, G. (2023). Effect of different cooling pad materials on the performance of the evaporative cooler. *Journal of Refrigeration, Air Conditioning, Heating and Ventilation, 10*(3).
5. Caleb, O. O., Olaiya, N. G., & Akintunde, M. A. (2019). Performance evaluation of a refrigeration system for fresh maize storage. *Journal of Engineering Research and Reports, 9*(4), 1–9.

6. Alghanima, Y. A., Mesalhy, O., & AbdelGawad, A. F. (2022). Effect of cold-side heat sink configurations on thermal performance of thermo-electric compartment of a hybrid household refrigerator. *Case Studies in Thermal Engineering, 37*, 102302. https://doi.org/10.1016/j.csite.2022.102302
7. Afshari, F., Ceviz, M. A., Mandev, E., & Yıldız, F. (2022). Effect of heat exchanger base thickness and cooling fan on cooling performance of air-to-air thermoelectric refrigerator: Experimental and numerical study. *Sustainable Energy Technologies and Assessments, 52*(B), 102178. https://doi.org/10.1016/j.seta.2022.102178
8. Suman, D., Prasad, P. S. H., Niranjan, K. N. V. S., Akhilesh, K., & Kumar, K. J. N. (2020). Design and fabrication of thermoelectric refrigerator using Peltier module. *Journal of Emerging Technologies and Innovative Research, 7*(3), 606–610.
9. Asyiqin, N., Fadzly, M. K., & Talip, A. (2019). Thermoelectric portable mini fridge using Arduino Uno temperature control. *AIP Conference Proceedings, 2129*(1), 020145. https://doi.org/10.1063/1.5118153
10. Ong, K. S. (2016). Review of heat pipe heat exchangers for enhanced dehumidification and cooling in air conditioning systems. *International Journal of Low-Carbon Technologies, 11*(3), 416–423. https://doi.org/10.1093/ijlct/ctu029
11. Ai, C., Xue, S., Zhang, L., & Zhou, Q. (2024). Research on the effect of water-cooling steel pipe on preventing spontaneous combustion of coal pile and its thermal migration behavior. *Scientific Reports, 14*, 8838. https://doi.org/10.1038/s41598-024-58857-3

INFLUENCE OF POST-WELD HEAT TREATMENT ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF ELECTRIC ARC WELDED MILD STEEL JOINTS

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Abstract

Mechanical and microstructure properties of weld joint between mild steel plates before and after heat treatment process have been studied. In this study, electric arc welding was used as a welding method as it is the most common welding method. Then heat treatment of the samples were done in the furnace. Firstly, in the heat treatment process, stress annealing was done as stress generated at different places in the welding zone and after that full annealing was done using furnace cooling for cooling purpose. Tensile strength was measured using ASTM A370 standard specimen and Brinell hardness test was done at different surfaces of the welding zone. The microstructures were observed by cutting the specimen in a certain shape, and mirror surfaces were generated to observe in electron microscope. From the results, it was observed that PWHT causes a 4.1 % increase in tensile strength, a 13.84 % gain in yield strength, and a 4.96 % rise in percentage elongation. However, the value of hardness decreased 19.19 % after heat treatment as heat treatment increased the ductility of the specimen. At the place of the Electric Arc Welding joint, a smaller grain size, a lower gap between the grains, and comparatively few voids were identified.

Introduction

Welded joints are crucial in many industries like construction, manufacturing, and transportation. They provide strength and durability to different parts, ensuring safety and reliability. It's important to understand the factors that affect the mechanical properties of welded joints for better design and performance. Welding is widely used in various industries, including construction, automotive, and aerospace. It involves fusing metal parts to create a strong bond for structural integrity. The mechanical properties of welded joints, like tensile strength, are vital for ensuring the safety and reliability of structures. The microstructure of the welding zone also plays a significant role in determining the joint's strength and resistance to failure. One important problem in welding is creating strong weld joints that can withstand impacts. The strength of a welded joint is crucial when the structure faces dynamic loads. However, the impact strength can be affected by different factors like welding settings, material properties, and heat treatment. To address this, it is necessary to study the impact strength of the welding area in steel joints and understand how the microstructure changes with heat treatment. Even though welding is widely used, there are still challenges in understanding how heat treatment affects the structure. When welding, heat is applied, causing melting in specific areas that quickly cool down, leading to changes in the structure.

These changes can significantly influence the joint's mechanical properties, making it imperative to investigate the correlation between microstructure and tensile strength. Several studies have looked into the use of post-weld heat treatment (PWHT) on joints created by different welding methods. Study of Ahmad & Bakar [1] observed that for post-weld heat treatment in GMAW welding process provided a significant improvement in the mechanical properties of welding joint. Water quenching and artificial hardening improved the hardness and tensile strength property by 20 % and higher elongation but crack can be formed in the welding joints due to rapid cooling in oil quenching [1]. Vairamani *et al.* conducted a study on the influence of post-heat treatment during MAG welding on Corten steel joints, revealing significant improvements in the impact strength and hardness of the joints due to the heat treatment process [2]. Another study exhibited improvement on the ductility property of the Aluminum Alloy weld joint after using Solution Treating Titanium Water Quench (STA) in Hybrid Laser TIG welding [3]. Above mentioned studies depicted heat treatment process using oil quenching and water quenching while the current study focuses on furnace cooling and change in mechanical characteristics using electrical arc welding. To examine the impact of heat treatment on welded objects that changes internal molecular structure of any metal Singh *et al.* [4] explored how post-welded heat treatment impacted the microstructure, mechanical properties, grain structure, hardness, and tensile strength of friction stir-welded joints with AZ31 Mg alloy. Few studies identified that suitable heat treatment led to finer grain structures, enhanced and stable mechanical properties, and increased joint strength [4,5]. Ahmad & Bakar observed that PWHT gives finer and smaller grain size and smaller gap between the grains in GMAW [1]. Wang *et al.* [6] found that, STA treatment provides fine equiaxed grain and a small number of columnar crystals in Hybrid Laser-TIG welding. Proton *et al.* [7] emphasized that postweld heat treatment plays a crucial role in improving the corrosion behavior of friction stir-welded joints made from a 2050-T3 aluminum-copper-lithium alloy by reducing the likelihood of localized corrosion while enhancing the joint's structure, resistance to corrosion, and strength.

Moradi *et al.* [8] studied how pre- and post-weld heat treatment affected the structure, strength, and intermetallic phase formation in SiC-reinforced dissimilar AA6061AA2024 butt joints made with friction stir welding (FSW), highlighting the importance of appropriate heat treatment for optimizing the mechanical performance of these joints by refining the structure and reducing detrimental intermetallic phases. Vicente *et al.* [9] investigated on the oxidation and porosity phenomena in weld joints between Fe-Cr-Al alloy (23Cr-7Al) and AISI 310 austenitic stainless-steel using gas tungsten arc welding method and the results were observed in isothermal heat treatment condition in air. Wang *et al.* [6] observed that post- welded heat treatment at room temperature improves ductility of the weld zone of Ti-23Al-17 Nb alloy using laser beam welding method. Zhang *et al.* [10] studied the microstructure and tensile strength properties of friction stir welded 2195-T8 Al-Li alloy with variation of welding parameters like rotation speed and welding speed. Post heat treatment observations were also investigated. Microstructure and corrosion behavior of AA2219 aluminum alloy using variable polarity tungsten inert gas welding process and the effects shown after heat treatment process by Zhu *et al.* [11] Apart from this discussed literature, [12-17] also illustrated the mechanical properties and microstructure for aluminum and streel joints after applying different welding approaches. The existing literature highlights numerous studies that have explored the microstructural and mechanical characteristics of various welded materials using different heat treatment methods.

Most commonly, researchers have employed Gas Metal Arc Welding (GMAW) and Laser Tungsten Inert Gas (TIG) welding techniques. To the best of authors' knowledge, there appears to be a gap in research when it comes to analyzing the impact of Electric Arc Welding (EAW) combined with a specific heat treatment process, namely Annealing, on mild steel joints. Therefore, it is imperative to undertake a systematic investigation to ascertain how various parameters of Post-Weld Heat Treatment (PWHT) influence the microstructural and mechanical properties of mild steel joints created through (EAW). Thus, this study endeavor aims to delve into the consequences of altering PWHT parameters on the mechanical properties, microstructure, and residual stress levels in EAW joints of mild steel.

The primary goal of this study is to assess the tensile and impact strength within the weld zone of mild steel joints and evaluate the alterations in microstructure resulting from the heat treatment process. The insights gained from this study will be beneficial to engineers, researchers, and professionals in the industry, offering valuable insights into enhancing the design, production, and performance of welded structures. Furthermore, this research has the potential to contribute to the advancement of supercritical and ultra-supercritical boilers for thermal power plants.

Table 1: Welding parameters

Welding pass	Welding current (A)	Arc voltage (V)	Travel speed (mm/s)	Heat input (kj/mm)
1st pass	120	19.3	65	1.05
2nd pass	110	18.8	65	.92

Table 2: Chemical composition of filler

Material	E6012
Mild Steel	98 %
C	0.1 %
Mn	0.5 %
Si	0.3 %
S	0.35 %
P	0.40 %

Table 3: Chemical composition of mild steel sample

Material	Percentage
Carbon (C)	0.17 %
Manganese (Mn)	0.54 %
Silicon (Si)	0.2 %
Phosphorus (P)	0.16 %
Iron (Fe)	98.7 %

Figure 1: (a) root pass, (b) welded samples (c) electrodes used, (d) arc welder, (e) top view of the plate, (f) root view of the plate.

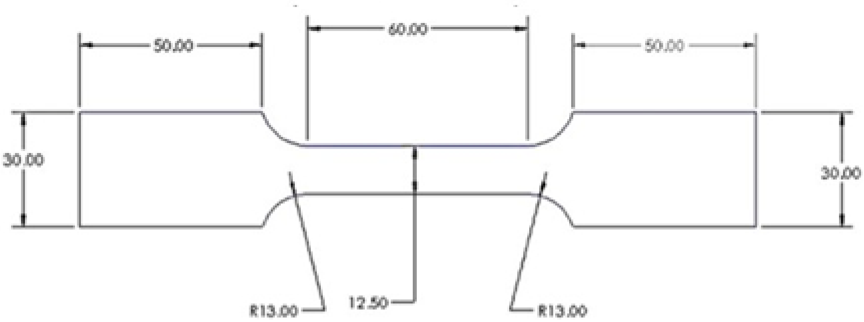


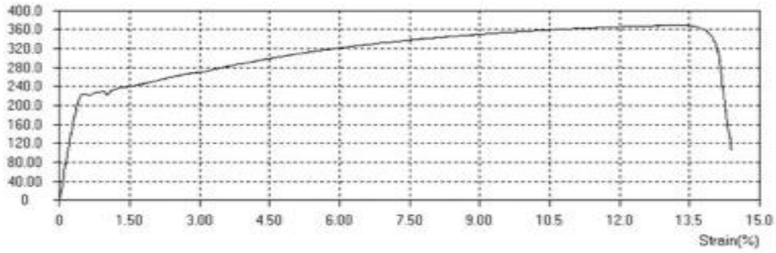
Figure 2: ASTM A370 mild steel sample design

(a)

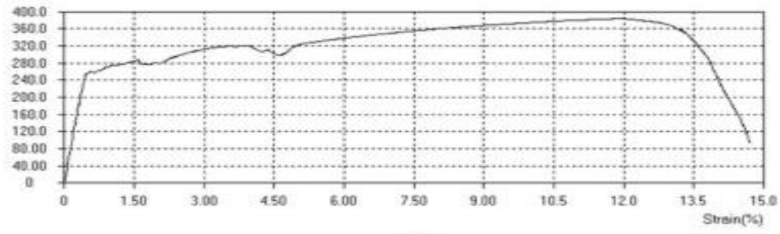
(b)

(c)

Figure 3: (a) as welded steel specimen (b) heat treated weld specimen (c) fractured specimen.



(a)



(b)

Figure 4: Stress-Strain Curve for (a) as welded and (b) heat treated samples

Methodology

The material used in this experiment was mild steel plates with a thickness of 5 mm. Table 2 and Table 3 highlight the chemical properties of the materials. Before starting the welding process, the material was cleaned with ethanol to get rid of any dirt or contaminants. The steels were connected using electric arc welding. It involves creating an electric arc between an electrode and the work piece, which generates intense heat to melt the base metals. Table 1 highlights the welding parameters maintained in this study while Fig. 1 presents the welding processes of the study. The welding procedure made sure that the plates were correctly positioned and fitted together, resulting in a powerful weld connection. The heat treatment process had two main steps. First, the sample was subjected to stress annealing at a temperature of 540 ◦C for 1 h, and then it was cooled in a furnace. After that, a full anneal was done at a temperature of 850 ◦C. The sample was kept at this temperature for a specific period and then cooled in a furnace. The ASTM 370 guideline was used to shape the samples according to specific requirements for the tensile test, guaranteeing they were consistent and met the desired standards. The geometry of the sample is presented in Fig. 2. A universal testing machine (UTM) is a flexible mechanical device that is used to examine the characteristics of materials, including how strong they are and how much they can stretch. In this study, a UTM was employed to perform a test on steel plate samples that had been welded together. The UTM applies a controlled force to the sample and measures how much it stretches or changes shape. This test gives us the tensile strength of the samples. The hardness of the samples was measured using a special device called a Rockwell, Brinell, and Vickers (RAB) hardness tester. This test helped determine how resistant the material was to being indented. The hardness test includes putting a certain amount of pressure on the material and measuring the depth or size of the resulting indentation. An electron microscope was used to study the microstructure of welded steel plates. 200x magnification was done to observe the microstructure of the welded samples. This analysis helps us see the internal structure, grain boundaries, and any changes in the structure caused by the heat treatment process.

Result and Discussion

Tensile Strength Test

The tensile test result is shown in Fig. 4 and the standard sized specimens and the fractured samples are shown in Fig. 3. The tensile strength values for the PWHT and as-welded samples were 384 & 369 MPa respectively. An increase of 4.1 % in the tensile strength is seen from the results. Also, an increment of 13.84 % in yield strength is found which changes from 224 MPa to 255 MPa. According to Fig. 5, the percentage of elongation was calculated at an average value. PWHT and as welded samples had elongation percentages of 14.8 % and 14.1 %, respectively. hence, PWHT applied to the samples enhanced the elongation percentage by 4.96 %. Higher tensile strength, and elongation results demonstrate how PWHT added to electric arc welded joints is superior to aswelded mild steel joints. This might be explained by the fine and homogeneous distribution of particles that are produced at the weld joints when PWHT is applied. It was discovered that PWHT joints have superior tensile and elongation properties because the weld metal region of these joints has a very fine and homogeneous distribution of precipitates when compared to other joints.

Hardness Test

The values of Brinell hardness test were taken from four different positions in top of the welding zone which are shown in Fig. 5. Hardness strength was measured before and after the heat treatment process. The results from the experiment are shown in Table 4. From the values we can define that the hardness value is greater in case of pre heat treatment process. On the other hand, the Brinell hardness value in the welding zone in the post heat treatment process is less than hardness value of pre heat treatment process. The hardness number is highest in case of pre heat treatment process and the values are all the same at four different positions of the welding zone and the hardness number is 187 in BHN. In case of post heat treatment, the hardness values are less than the previous. The values are 156 in Brinell hardness scale and at 2nd point we get the lowest hardness number and that is 131. That means this point had the lowest hardness value. The change in hardness number between pre heat and post treatment process is in average 19.19 %.

Microstructure Analysis

Fig. 6a, b and c show the typical cross-sectional microstructures of different regions of the sample before heat treatment. There are 3 regions found in the microstructure of the sample before heat treatment. These regions are: Refined zone that contains a fine and small grain, Coarsened zone that contains less dense grain and Lastly, Metal Deposited zone that contains bigger grain with column type structure. After completing two steps annealing, an α-ferrite matrix(white) with uniformly spaced pearlite regions(dark) all over the specimen was observed. Ferrite is relatively soft and ductile, while pearlite is a mixture of ferrite and cementite (Iron Carbide) layers. The microstructure provides moderate strength and hardness. The distribution and morphology of ferrite and pearlite can vary depending on factors such as the cooling rate during solidification, hot rolling, and subsequent processing steps. It includes spheroidized pearlite as it consists of spherical or globular cementite particles embedded within a ferrite matrix. During annealing, the steel is heated to 540 ◦C first and furnace cooled then 850 ◦C. to modify the microstructure and properties. After annealing the joint, the microstructure is achieved with a refined form of pearlite. After annealing shows promotion of the formation of fine pearlite. Fine pearlite consists of alternating layers of ferrite and cementite that are more closely spaced compared to the microstructure before any heat treatment shown in Fig. 6. We can define that the hardness value is greater in case of pre heat treatment process. It is due to the needle-like microstructure that creates stress concentration points in the welded region.

Table 4: Hardness value for different situations

Sample	Point 1	Point 2	Point 3	Point 4
Pre heat treated	187	187	187	187
Post Heat treated	156	131	156	156

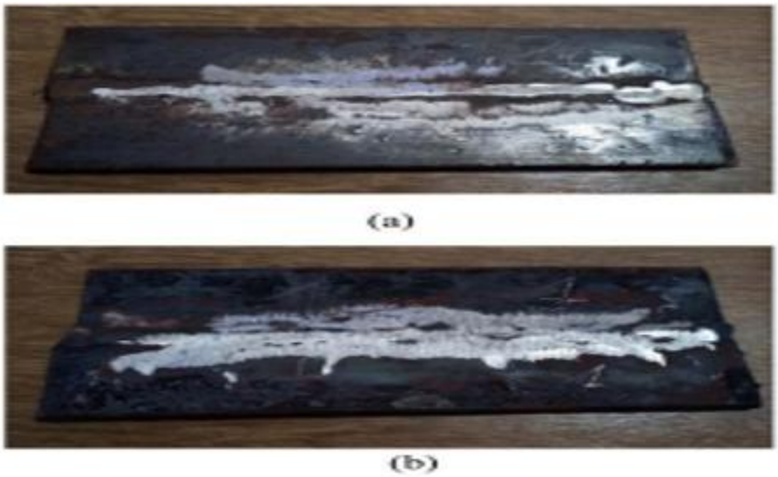


Figure 5: Hardness test specimen (a) as welded and (b) heat treated samples

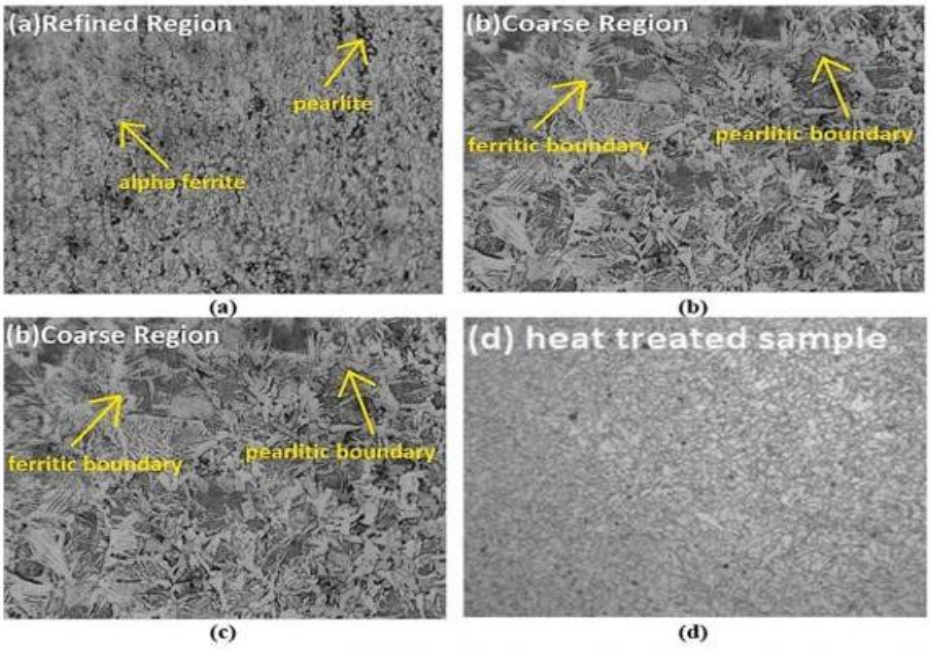


Figure 6: Microstructures (a) as welded refined region (b) coarse region (c) metal deposition region and (d) heat treated sample

On the other hand, as more refined microstructure is created through the heat-treatment process, the Brinell hardness value in the welding zone in the post heat treatment process is less than the hardness value of pre- heat treatment process. The lamellae of cementite and ferrite become smaller and more uniformly distributed, resulting in such a refined microstructure. With an improving ductility, the fine pearlite microstructure provides better toughness and formability, making the weld joint more suitable for cold working or forming processes. The smaller and more uniform pearlite grains result in reduced tool wear during machining operation and improved surface finish.

Conclusion

The microstructure and mechanical characteristics of electric arc welded mild steel joints were experimentally examined by applying post weld heat treatment. The key findings of this study are as follows: i. Due to PWHT, Tensile strength is increased by 4.1 % along with 13.84 % increment in Yield Strength and 4.96 % enhancement in percentage elongation. However, the hardness is reduced 19.19 % after heat treating. It proves that PWHT is suitable for increasing the tensile strength of the mild steel but not ideal for Hardness of mild steel. ii. PWHT produces very fine and homogeneous distribution of particles at the weld joint which increases the ductility of the joint and thus increment in tensile strength, yield strength and percent elongation and reduces the brittleness properties thus the Hardness number. iii. A smaller grain size, a smaller gap between the grains and relatively small voids were observed for the Electric Arc Welding joints. These qualities led to the superior tensile properties, compared with the as-welded joint. iv. The welded mild steel is more suited for cold working or forming processes because of its increased ductility, improved toughness, and improved formability provided by the fine pearlite microstructure. Reduced tool wear and improved surface finish are obtained due to the smaller and more uniform pearlite grains during machining processes.

References

1. Ahmad, R., & Bakar, M. A. (2011). Effect of a post-weld heat treatment on the mechanical and microstructure properties of AA6061 joints welded by the gas metal arc welding cold metal transfer method. *Mater. Des., 32*(10), 5120–5126.
2. Vairamani, V., Mohan, N., Karthikeyan, S. K., & Sakthivel, M. (2020). Optimization and microstructure analysis of Corten steel joint in MAG welding by post heat treatment. *Mater. Today: Proc., 21*, 673–680.
3. Wang, H., Liu, X., & Liu, L. (2020). Research on laser-TIG hybrid welding of 6061-T6 aluminum alloys joint and post heat treatment. *Metals, 10*(1), 130.
4. Singh, K., Singh, G., & Singh, H. (2021). Influence of post welding heat treatment on the microstructure and mechanical properties of friction stir welding joint of AZ31 Mg alloy. *Proc. Inst. Mech. Eng., Part E: J. Process Mech. Eng., 235*(5), 1375–1382.
5. Du, C., Wang, X., & Luo, C. (2019). Effect of post-weld heat treatment on the microstructure and mechanical properties of the 2205DSS/Q235 laser beam welding joint. *J. Mater. Process. Technol., 263*, 138–150.
6. Wang, G. Q., Wu, A. P., Zhao, Y., Zou, G. S., Chen, Q., & Ren, J. L. (2010). Effect of post-weld heat treatment on microstructure and properties of Ti-23Al-17Nb alloy laser beam welding joints. *Trans. Nonferrous Met. Soc. China, 20*(5), 732–739.

7. Proton, V., Alexis, J., Andrieu, E., Blanc, C., Delfosse, J., Lacroix, L., & Odemer, G. (2011). Influence of post-welding heat treatment on the corrosion behavior of a 2050-T3 aluminum-copper-lithium alloy friction stir welding joint. *J. Electrochem. Soc., 158*(5), C139.
8. Moradi, M. M., Aval, H. J., & Jamaati, R. (2017). Effect of pre and post welding heat treatment in SiC-fortified dissimilar AA6061-AA2024 FSW butt joint. *J. Manuf. Process., 30*, 97–105.
9. de Albuquerque Vicente, A., Moreno, J. R. S., Espinosa, D. C. R., de Abreu Santos, T. F., & Tenorio, J. A. S. (2019). Study of the high temperature oxidation and Kirkendall porosity in dissimilar welding joints between FE-CR-AL alloy an isothermal heat treatment at 1150C in air. *J. Mater. Res. Technol., 8*(2), 1636–1644.
10. Zhang, J., Feng, X. S., Gao, J. S., Huang, H., Ma, Z. Q., & Guo, L. J. (2018). Effects of welding parameters and post-heat treatment on mechanical properties of friction stir welded AA2195-T8 Al-Li alloy. *J. Mater. Sci. Technol., 34*(1), 219–227.
11. Zhu, Z. Y., Deng, C. Y., Wang, Y., Yang, Z. W., Ding, J. K., & Wang, D. P. (2015). Effect of post weld heat treatment on the microstructure and corrosion behavior of AA2219 aluminum alloy joints welded by variable polarity tungsten inert gas welding. *Mater. Des. (1980–2015), 65*, 1075–1082.
12. Chen, Y. C., & Nakata, K. (2008). Effect of the surface state of steel on the microstructure and mechanical properties of dissimilar metal lap joints of aluminum and steel by friction stir welding. *Metall. Mater. Trans. A, 39*, 1985–1992.
13. Li, H., Zou, J., Yao, J., & Peng, H. (2017). The effect of TIG welding techniques on microstructure, properties and porosity of the welded joint of 2219 aluminum alloy. *J. Alloy. Compd., 727*, 531–539.
14. Xie, J., Chen, Y., Yin, L., Zhang, T., Wang, S., & Wang, L. (2021). Microstructure and mechanical properties of ultrasonic spot welding TiNi/Ti6Al4V dissimilar materials using pure Al coating. *J. Manuf. Process., 64*, 473–480.
15. Haddadi, F., Strong, D., & Prangnell, P. B. (2012). Effect of zinc coatings on joint properties and interfacial reactions in aluminum to steel ultrasonic spot welding. *JOM, 64*, 407–413.
16. Akhter, R., Ivanchev, L., & Burger, H. P. (2007). Effect of pre/post T6 heat treatment on the mechanical properties of laser welded SSM cast A356 aluminium alloy. *Mater. Sci. Eng.: A, 447*(1–2), 192–196.
17. Garrett, R. P., Lin, J., & Dean, T. A. (2005). An investigation of the effects of solution heat treatment on mechanical properties for AA 6xxx alloys: Experimentation and modelling. *Int. J. Plast., 21*(8), 1640–1657.

GREEN SYNTHESIS AND CHARACTERIZATION OF CADMIUM NANOPARTICLES USING *CITRUS SINENSIS* SEED EXTRACT

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Abstract

Green nanomaterials are a promising strategy for making bioactive nanoparticles without any harmful reducer and/or stabilizer usage at all levels. Plant polyphenols are very attractive because they contain elements such as phenolics, flavonoids, sugars minerals salt forms proteins etc. In the present chapter, an aqueous extract of Citrus sinensis (orange) seeds is proposed as a biogenic reducing and stabilizing agent for the synthesis of cadmium nanoparticles (CdNPs), with emphasis on reproducibility, characterization, and biological evaluation. Plant-based synthesis methods for metal production have been widely used because these factors such as solvents used while reacting with reactants vary depending on their concentration levels across a range of acidities; temperature values associated therewith. Also, oranges derived matrix is capable of containing biologically active substances that can be reduced/stabilized recently there were reports on orange-pellicle induced Nano-materials through GC-MS based Phytochemistry analysis as well as characterization via UV-vis, TEM & EDX techniques.

Keywords: *Citrus sinensis*, Orange Seed Extract, Green Synthesis, Cadmium Nanoparticles, Phytochemicals, GC-MS, UV-Vis Spectroscopy, TEM, EDX, Antibacterial Activity.

1. Introduction

There is a persistent interest in nanomaterials as they are quite dissimilar to solid-state substances. Specifically, metals as well their Nano-forms are more reactive at a molecular level; they have higher activity for reactions (catalysts). Traditional synthesis methods use powerful reducing agents, organic solvents, and surfactants which are more expensive, toxic, and polluting1. On contrary to that, green synthesis is based on bio-renewables which make it easier for manufacturing as well as more compatible with biology [2]. Green reducing plants extract is one of those that have been researched a lot as its readily available, along with being highly chemical-based. Metabolites of there are electron donors that help detoxify metals, as well as surface-active agents which prevent clustering among themselves [3]. Green chemical synthesis papers stress on factors like solvents used for extracting materials; their concentrations; temperatures of reactions etc.; as well as conditions such as acidity levels during a process affecting sizes, shapes & stabilities of nanoparticles produced by this method are important parameters to consider [4].The orange oil derivatives were extensively studied as a precursor of Nano-materials; however, research on oranges has shown by means like gas chromatography-mass spectrometry (GC-MS) identification of essential oils which may be responsible towards decreasing/retention levels [5]. Although your project description alternates between peel and seed, the workflow below is written for the seed extract you requested, while still drawing on orange peel literature for methodological guidance and justification [6]. This paper is about citrus sinensis seeds extract, which acts as a bioactive substance. While you are describing a process that involves both peels as well seeds; this procedure has been developed to address an issue of extracting seeds from oranges rather than shells [7].

2. Rationale and Scope

The orange seed is a crop residue which could easily extracted from farming process, turned out as valuable product. Seed extract as a reducer/capping agent is consistent with circular economy practices, which might result in lower costs than synthetic stabilizers. Citrus products are bioactive, that is why they can be used as a substrate to synthesize nanoparticles due their multivalent nature that interacts well with metals while forming nuclei/growth phase interactions. The orange peels as well as similar oils of citrus are acting now [8].

This paper's primary purpose was developing an experimental protocol that would enable synthesis of Cd-nanoparticle from citrus seed extracts as well establishing standards regarding their properties [9]. It includes a section on evaluating antimicrobial efficacy for comparison between Nano-formulations of extracts vs traditional formulations [10]. Earlier a bioactive plant extract mediated approach was used for controlling cadmium contamination [11] it was found that water soluble extracts are stabilizing precursors which lead to nanoparticle formation. It is deliberately applied wider scope of study. There is no assumption of an idealized nanoparticle phase since it depends upon the cadmium precursor utilized as well as reaction parameters. For elemental Cadmium Nano particles use appropriate parameters since its labile/oxidative nature need to be considered [12] while preparing precursors.

3. Materials and Methods

3.1 Plant Material Collection and Authentication

The ripped citrus sinensis fruit were procured from fruit supplier, then it is stored with proper packing materials available in the lab. The seeds must also be hand-seeded with lot of pulp get attached which in turn needs washing by tap water, after which it is washed 2-3 more times with distilled water and dried properly in the hot air oven. The seeds then scientifically identified and labelled by botanist and the specimen must be deposited in recognised departmental archieve with seed lot number, time of harvest & storage parameters as this information provides the details whether the samples obtained from organically grown fruits [13] or purchased fruit markets or industrial by-products of fruit processing.

3.2 Preparation of Seed Powder

The seeds are washed and dried. The drying process can be made air-dried in the shade at ambient temperature for several days or oven-dried at a low temperature, typically not exceeding 45-50 °C, to avoid decomposition of thermos labile phytochemicals [14]. After attaining steady weights, grind them to fine grains with an efficient machine of your choice for processing purposes. If you need a consistent grain size of your material, sieve it out first before storing then it is again dried in sunlight [15] for the final drying process. Fresh wet mass is compared with dried weight mass after drying, to remove moisture content. This is important as it relates to the particle size of a feed material, which affects its ability to dry out effectively.

3.3 Aqueous Extract Preparation

A water-soluble solution should be used during the process of biosynthesis as it is cheaply available, safe to use, suitable for various post-processing steps. About 10 g of dried seed powder is dissolved in 100 mL of double-distilled water in a round-bottom flask. Reflux the mixture at 80-90 °C for 30-60 minutes with gentle stirring. After cooling to room temperature, filter the resultant through muslin cloth and then through whatman filter paper. The filtrate must be kept in amber bottles and stored at 4°C until use.

Optimization for extraction needs to happen prior-to-nanoparticles preparation as there are fluctuations within concentrations of reduced substances based upon temperatures involved during this process. For preparing different concentration of this solution use evaporation technique with low vacuum conditions as well as freeze drying technique followed by dissolving it again to an established strength. To conduct a comparative study, we should prepare several extracts at various temperatures like cooling process, refluxing & boiling etc., also note out yields from these samples along with their acidity levels. Prior reports on plant-mediated nanoparticle synthesis indicate that extraction temperature and solvent system directly influence the reducing and capping capacity of the extract.

3.4 GC-MS Analysis of the Extract

The GC-MS method must also be performed for detecting of volatiles as well non-volatiles present from boiling water extracts. The sample must be lyophilized to remove water and suspended impurities and then suspended in suitable column with an appropriate stationary phase (GC) before analysis. Column properties like a type of sample; conditions such an inert mixture has to be maintained. A small fraction of the sample is injected directly to detector (split). Even minor alterations of GC-MS settings may affect identification of compounds largely. Compare the spectrum obtained to libraries like NIST &WILEY for matching results; report just those that are highly probable matches of yours. In the discussion, link the identified compounds to possible reducing functional groups such as hydroxyl, carbonyl, carboxyl, and ether functionalities. The orange peel research has demonstrated that GC- mass could identify several plant chemicals pertinent for Nano-particle production, hence it is an effective resource utilization tool for citrus residues.

3.5 Cadmium Precursor and Safety

Depending upon synthesis method the most commonly employed labile Cd precursors for use as a reagent are Cd Chlorides, Nitrates & Acetates all of these reagents will have some advantages and disadvantages. Since it's extremely poisonous, all the reactions must be performed under exhaust fan as well wearing gowns, masks for eyes & hands. Do not dump cadmium contaminated materials anywhere near a lab drain, nor mix it up other garbages. Cadmium products must be stated as being managed by institution's chemistry department. In consideration of the above facts that researchers use "green" process to synthesize cadmium compounds. Plant extracts function like reducing agent.

3.6 Green Synthesis of Cadmium Nanoparticles

For a standard synthesis, prepare an aqueous solution of the cadmium precursor at a known concentration, such as 1-10 mm depending on optimization needs. Place the solution on a magnetic stirrer and heat it to the chosen reaction temperature, typically 25-80 °C. Drop of orange seeds extract gradually while stirring continuously. The extract-to-precursor ratio should be systematically optimized, so that it gives the most stable colloid and narrow particle distribution. Observe it visually to see any change of colour. Since bioactive compounds are very susceptible of being affected by a change on acidity level then mix it up with weak solutions like 0.1m sodium hydroxide (NaOH) for basicity; 0.1m HCl as acidifying agent. PH also noted as there is a large variation between particles of varying sizes, depending on their acidity levels. An accomplished reaction is suggested through an enduring color change, constant UV-Vis signal, and no quick precipitation. Afterwards wait until it has matured before dissolving again as needed. Collect the nanoparticles by centrifugation at 8,000-15,000 rpm for 10-20 minutes, wash repeatedly with distilled water and, if needed, ethanol to remove unbound hytochemicals, then dry at room temperature, in a vacuum desiccator, or in a lyophilizer. The drying method should be specified because high heat can alter nanostructure or oxidize surfaces. Keep it as dry powders inside glass bottles with an oil bath, under refrigeration conditions for analysis purposes.

3.7 UV-Visible Spectroscopy

The UV-Vis spectrophotometer can be used as a primary instrument to monitor nanoparticle production process. Measure the colloidal suspension in quartz cuvettes over a suitable scan range, usually 200-800 nm. Contrast spectral data of a cadmium salt, an extraction product as well as its mixture with other substances. An additional phase-boundary related absorption peak, as well an obvious change of spectrum with respect to adding solvents are indicative for nanoparticle formation. Exact wavelengths depend upon material as well environment; therefore, this book does not state any particular values for these parameters except those that were determined by experiments. Please report on a spectroscopic data of your sample with respect to wavelengths as it will help determine kinetics & stability for suspension particles. Reproducibility is improved if scans are taken at set intervals such as 0, 15, 30, 60, 120, and 180 minutes. Correlate any observed differences between spectra of a given substance under varying conditions (pH & temperatures) for optimal catalytic activity towards its formation.

3.8 FTIR and Surface Chemistry

FTIR is used to compare between constituents of a raw material as well as products formed by synthesis. Samples are analysed with KBr powder using ATR technique. Changes between a band that corresponds with OH group (hydroxyl), and a doublet at 170-180 cm^{-1} for a carbonyl group, another triplet around 165-175 cm^{-1} representing Carboxyl group. The interpretation of the peak changes with maximum height, strength & spread. For instance, an increase in O-H stretching frequency is indicative of hydrogen bonding and surface adsorption whereas changes in C=O signals are indicative of binding of polyphenols onto the nanoparticle surface. The molecular structure study is a complement of GC-MS that tells us about the functional group remains on the material during polymerization process.

3.9 XRD and Crystallinity

The X-ray analysis must also have been done for determining its crystal nature as well identification of phases obtained from an existing cadmium salt sample. Samples should be scanned over a suitable 2θ (two-theta) angle range, usually around 10-80 degrees, with an appropriate step size and scan speed. The diffraction pattern obtained should match with reference data for identification of crystalline nature. For crystal grain size determination use of Scherer's formula on the strongest peak which is corrected instrumentally if the broad peak occurred, in order to get good result the peak should be narrower. XRD does not represent the actual size as seen from transmission electron microscopy (TEM).

3.10 TEM, SEM

TEM can also help with determining morphology of particles as well their size distribution & dispersing states. The specimen should be prepared as follows a drop of diluted Nano particles onto coated carbon copper grids and it is allowed to air dried before analysis purposes. Measure at least 100 Nano particles from multiple micrographs to produce a meaningful size distribution. Get the report of Median particle size and variation in particle sizes using Standard deviation, shapes like sphere, ellipsoid, needle etc. SEM can also measure surface topography and aggregation. EDXA demonstrates presence of Cd, as well as its other elements present on a given material specimen. Carbon-rich cap layers are present if there are carbon and oxygen peaks occurs. The orange derived green-synthesizing researches usually use UV-Vis technique, TEM as well EDX for verifying Nano-materials existence along with element analysis.

3.11 Antibacterial Evaluation

The antibacterial test must be performed to evaluate the bacterial activity of synthesized nanoparticle using gram positive as well as gram negative organisms through conventional bacteriology techniques. Some of them are Staphylococcus aureus, Bacillus subtilis, Escherichia coli & Pseudomonas aeruginosa. Agar well diffusion method may also help to screen out bacteria using MIC (Minimum Inhibitory Concentration) & MBC (Minimum Bactericidal Concentration) tests. Prepare bacterial culture at the 0.5 McFarland standard. Inoculate Mueller Hinton agar plate evenly for diffusive assays using disk method with pre-filled volume extracts nanoparticles. Measure zones of inhibition after incubation at 37 °C for 18-24 hours. Since certain herbal extracts have been found to be more active than nanomaterials, this section must contrast them with each other as well as those precursors. The orange-pelleted Nano-formulations are also effective against bacteria as per current researches; furthermore, reviews indicate biological sized particles perform better than natural ones because of greater surface reactivity.

3.12 Cytotoxicity and Biocompatibility

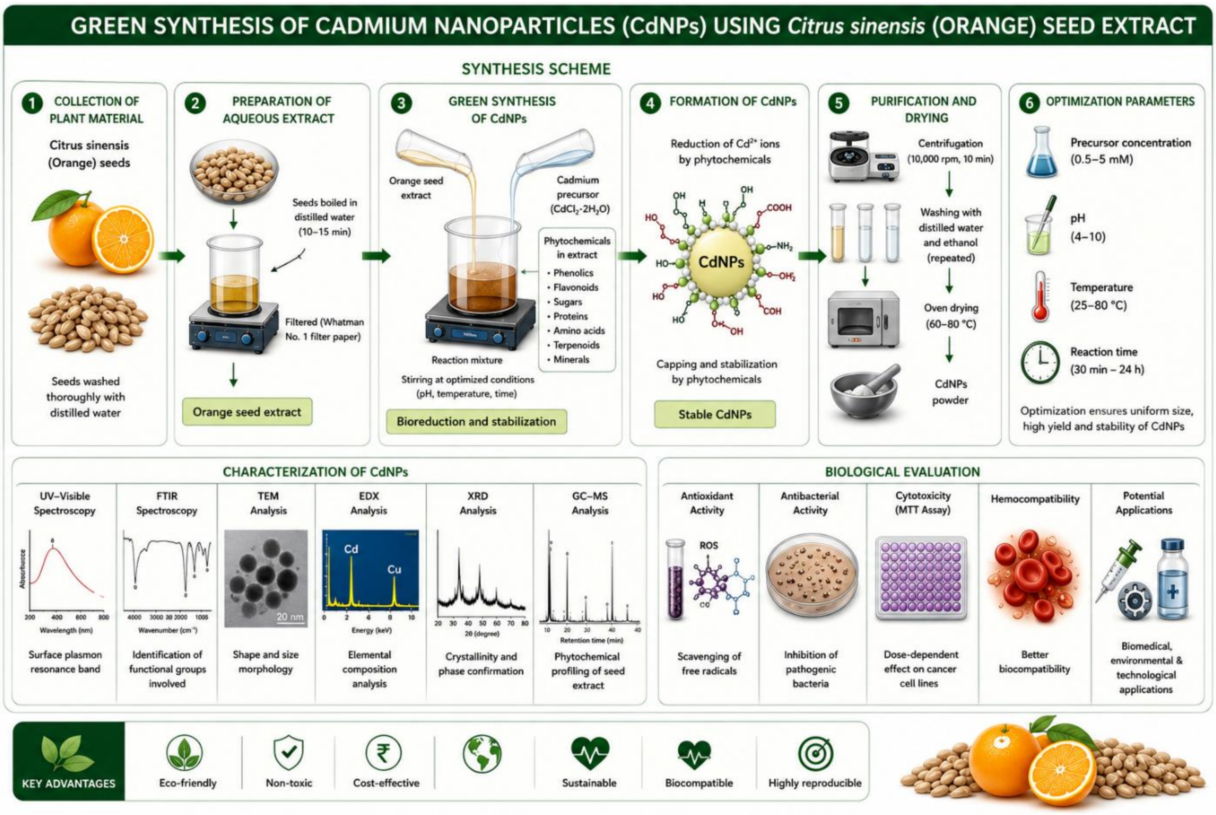
Since it is poisonous, cytotoxicity test should be conducted. When you have a facility for culturing cells tests like MTT assay, Resazurine staining &Trypan blue exclusion assay should be performed using two/3-4 selected lines. Both, synthesized green extract as well as raw extracts should be included for comparison of their toxicities. The study are carried out with different concentrations, there are also control samples as well replicates needed for this experiment. The test is carried to test the amount of toxicity and guaranteeing security for everyone involved with it. Previously conducted research on CdS plants extracts showed differences between extracts as well as nanoparticles concerning their antibacterial activity levels; however, they were generally more poisonous when taken together compared to individual components separately.

4. Expected Results and Discussion

With proper implementation of the experiment correctly we get dark coloured substance from yellow colour and this confirms the formation of nanoparticles. A full spectrum of UV and a TEM image confirm the formation of nanoparticles, FTIR carried out for elemental analysis (CdS). TEM images to confirm the particles is spherical. The GC-MS data from boiling citric acid revealed volatile/semi volatile phytochemicals. Orange-peeled fruit products support this as they contain active ingredients of oranges that can reduce and/or agglomerate particle sizes. However, there are exceptions as well some extracts may be more active due to their own bioactive ingredients. Nanoparticles are much harmful as compared to suspensions since their size allows easy penetration of membrane which makes them highly susceptible at point of application. Nevertheless, it’s particularized as well; some parts are perhaps stronger due to their natural bioactivity. The research on a Nano system showed differences in terms of toxicity between both materials (plant extracts) to compare them one-to-one. A better strategy is to compare it with current research findings regarding plant extract nanomaterials rather than overstating innovations at an atomic level.

5. Safety and Environmental Issues

The cadmium is listed to be a dangerous substance and it should be used with. Since Cadmium solution is present in wastewater treatment effluent, filter media, gloves etc., discarding the products should happen under national/industrial standards. Care should be that the nanoparticles must not reach the lungs. Whenever there is direct contact with particles wash them with water instead of dry wiping them. While green chemistry minimizes hazardous chemicals like reducer/stabilizer usage; however, there is still a risk to health from cadmium. We should not draw the conclusion about environmentally friendly synthesized produced nanoparticle is free from toxins because for synthesis we use hazardous chemicals even though we use environment friendly orange seed extract.



Conclusion

The aqueous citrus sinensis seed extract is an attractive, inexpensive as well sustainable material to synthesize nanoparticles environmentally friendly way. Phytochemicals from this compound will help to lower cadmium precursor levels; they also prevent particle formation through these methods (pH, temperature). A rigorous workflow should combine phytochemical profiling, GC-MS, UV-Vis, TEM, EDX, and, where possible, XRD and FTIR to establish the identity and surface chemistry of the final product. Because cadmium is hazardous, the chapter should also emphasize safety, waste disposal, and careful interpretation of biological data. To be publishable it needs replicability details about materials used for growing plants; how were they extracted from them. For research papers to be published they must be able to reproduce the results with the experimental work provided in the information. The methodology includes the plant source, extraction conditions, synthesis parameters, purification steps, and assay protocols etc., Since Cadmium is hazardous, safe handling procedures and proper protection equipment (PPE) and proper disposal needed.

References

1. El Shafey, A. M. (2020). Green synthesis of metal and metal oxide nanoparticles from plant leaf extracts and their applications: A review. *Green Processing and Synthesis*, 9(1), 304–339
2. Hanna, M., Olawale, T., & Smith, J. (2026). Plant-derived nanoparticles: Green synthesis, key parameters, and emerging bioactivities. *Journal of Cleaner Production*, 412, 114–128
3. Mendonça, R., Silva, A. P., & Ferreira, L. (2023). Biosynthesis of nanoparticles using plant extracts and essential oils: Unveiling the chemical complexity of natural stabilizing matrices. *Molecules*, 28(9), 3740
4. Gómez-López, M., Al-Khafaji, Z., & Martínez, A. (2026). Green synthesis of copper oxide nanoparticles using *Citrus sinensis* leaf extract: Optimization of extraction solvent, precursor concentration, calcination temperature, and pH. *Nanomaterials*, 16(6), 369.
5. Santos, E., Ribeiro, D., & Costa, M. (2025). Citrus waste valorization: Unconventional pathways for sustainable extraction of volatile organic compounds and functional biomaterials. *Sustainability*, 17(24), 10887.
6. Srivastav, Y., Singh, J., & Bind, S. B. (2024). Plant-mediated synthesis of copper nanoparticles using *Citrus sinensis* extract: Structural characterization and comparative analysis of seed-to-shell processing paths. *Journal of Materials Research and Technology*, 38, 510–521.
7. Vanlalveni C, Lallianrawna S, Biswas A, Selvaraj M, Changmai B, Rokhum SL. Green synthesis of silver nanoparticles using plant extracts and their antimicrobial activities: a review of recent literature. *RSC Advances*. 2021; 11: 2804–2837.
8. Sayed, S. R., & El-Sayed, A. S. (2025). Valorization of *Citrus sinensis* seed processing waste: Extraction of water-soluble biomolecules as stabilizing capping matrices for eco-friendly nanomanufacturing. *Industrial Crops and Products*, 214, 118410.
9. Nguyen, T. H., & Kim, J. H. (2025). Controlled synthesis of biogenic cadmium nanoparticles: Managing precursor chemistry, oxidation lability, and phase transformation Cd to Cd $(CO)_3$ Materials Research Bulletin, 182, 112650.

10. Siddiqui, L., & Ahmed, S. (2025). Cytotoxic potentiality and cell-killing kinetics of green synthesized metal nanoparticles: Distinguishing the raw bioactive substrate from Nano-engineered complexes. Toxicology in Vitro, 96, 105820
11. Huang, L., & Zhang, Y. (2025). Biogenic synthesis of cadmium-based nanoparticles using water-soluble plant metabolites: Dual action of environmental remediation and capping stabilization. *Journal of Hazardous Materials*, 482, 136112.
12. Garcia-Serrano, J., & Rodriguez, M. (2026). Phase evolution and oxidation kinetics of elemental cadmium nanoparticles under atmospheric and aqueous conditions. *Materials Chemistry and Physics*, 312, 128450.
13. Ahmad, M., & Khan, M. A. (2025). Taxonomy, authentication, and standard operating procedures for voucher specimen deposition in green nanotechnology: Ensuring reproducibility in biogenic syntheses. *Phytochemical Analysis*, 36(2), 189–204.
14. Mendonça, R., Silva, A. P., & Ferreira, L. (2023). Biosynthesis of nanoparticles using plant extracts and essential oils: Unveiling the chemical complexity of natural stabilizing matrices. *Molecules*, 28(9), 3740.
15. Sayed, S. R., & El-Sayed, A. S. (2025). Valorization of *Citrus sinensis* seed processing waste: Extraction of water-soluble biomolecules as stabilizing capping matrices for eco-friendly nanomanufacturing. *Industrial Crops and Products*, 214, 118410.

PREPARATION TECHNIQUES FOR In_2S_3 THIN FILMS

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1. Introduction

Indium sulfide (In_2S_3) is one of the most important III–VI compound semiconductors owing to its excellent optical transparency in the visible region, suitable band gap, environmental compatibility, and remarkable chemical stability. Unlike cadmium-based semiconductors, In_2S_3 is comparatively less toxic, making it an attractive alternative for sustainable optoelectronic devices. Thin films of In_2S_3 have attracted considerable attention because of their applications as buffer layers in thin-film solar cells, photodetectors, photocatalysts, gas sensors, electrochemical devices, and photoelectrochemical cells [1-3].

The physical properties of In_2S_3 thin films are strongly influenced by the synthesis route employed. Parameters such as crystallinity, grain size, stoichiometry, surface morphology, thickness, defect concentration, and optical band gap depend on the deposition technique and process conditions. Consequently, selecting an appropriate synthesis method is essential for obtaining high-quality films with properties tailored for specific applications. Indium sulfide exists in several polymorphic forms, namely α-, β-, and γ-In_2S_3. Among these phases, β-In_2S_3 is thermodynamically the most stable at room temperature and is therefore the most frequently obtained during thin-film deposition. It possesses a defect spinel tetragonal crystal structure in which one-third of the tetrahedral cation sites remain vacant. These intrinsic vacancies significantly influence the electrical conductivity and optical properties of the material [4-5].

The formation of a particular phase depends upon several deposition parameters, including substrate temperature, precursor chemistry, sulfur availability, deposition rate, and post-deposition annealing. Films deposited at relatively low temperatures are often poorly crystalline or partially amorphous, whereas annealing promotes grain growth and phase transformation into well-crystallized β-In_2S_3.

Thin-film growth generally proceeds through nucleation, island formation, coalescence, and continuous film formation. During the initial stage, atoms or ions arriving at the substrate form stable nuclei. As deposition proceeds, these nuclei grow into islands that eventually merge to form a continuous layer. The dominant growth mechanism depends on the balance between surface energy, interface energy, and strain energy. Three classical growth modes are generally observed as Frank–van der Merwe (layer-by-layer growth), Volmer–Weber (island growth), Stranski–Krastanov (layer-plus-island growth). Solution-grown In_2S_3 films usually exhibit island growth during the initial stage, followed by lateral grain growth and coalescence. In contrast, vacuum deposition techniques often promote more uniform layer growth because of better control over deposition kinetics [6].

Numerous deposition techniques have been developed to prepare In_2S_3 thin films. These techniques can be broadly classified into chemical solution-based methods and vacuum-based physical deposition methods. Chemical methods are attractive because of their simplicity, low cost, scalability, and low-temperature processing, whereas physical deposition techniques generally produce films with superior crystallinity and excellent thickness control.

This chapter presents a comprehensive discussion of the major synthesis techniques employed for In_2S_3 thin films, emphasizing their working principles, reaction mechanisms, deposition parameters, growth kinetics, advantages, and limitations.

2. Chemical Bath Deposition (CBD)

The CBD process is based on the controlled precipitation of a sparingly soluble compound from an aqueous solution onto a suitably immersed substrate. The fundamental principle involves maintaining a supersaturated solution in which the release rates of metal cations and chalcogenide anions are carefully controlled so that heterogeneous nucleation on the substrate surface is favored over homogeneous precipitation in the bulk solution. In the case of In_2S_3 thin films, three essential components are required. The source of indium ions (In^{3+}), sulfur precursor capable of releasing sulfide ions (S^{2-}), and suitable complexing agent to regulate the concentration of free indium ions.

The complexing agent plays a vital role by reducing the concentration of free In^{3+} ions in solution. Without complexation, indium ions react immediately with sulfide ions, resulting in rapid precipitation of indium sulfide particles within the solution instead of on the substrate surface. By forming stable coordination complexes with In^{3+} ions, the complexing agent ensures their gradual release, thereby enabling controlled nucleation and continuous film growth. The substrate is immersed vertically or horizontally inside the reaction bath maintained at a predetermined temperature. As the reaction proceeds, the ionic product gradually approaches the solubility product (Ksp) of In_2S_3. Once supersaturation is achieved, nucleation begins preferentially on the substrate surface, followed by crystal growth until a continuous thin film is formed.

The deposition chemistry of In_2S_3 involves the controlled generation of indium ions and sulfide ions in the reaction bath. Common indium precursors include: indium chloride ($InCl_3$), indium nitrate [$In(NO_3)_3$], indium sulfate [$In_2(SO_4)_3$]. Among these, indium chloride is most frequently employed because of its high solubility and stable aqueous chemistry. Sulfur is commonly supplied by sulfur-containing compounds that slowly release sulfide ions upon hydrolysis. Frequently used sulfur precursors include: thioacetamide (CH_3CSNH_2), thiourea [$CS(NH_2)_2$], sodium thiosulfate ($Na_2S_2O_3$), sodium sulfide (Na_2S). Among these, thioacetamide and thiourea are preferred because they release sulfide ions gradually, allowing controlled film growth. Complexing agents commonly employed include: ethylene diamine tetra acetic acid (EDTA), triethanolamine (TEA), citric acid, tartaric acid, ammonia, sodium citrate. These ligands coordinate with In^{3+} ions to form soluble complexes that slowly dissociate during deposition [7].

The growth of In_2S_3 thin films by CBD generally involves four distinct stages. Initially, indium ions are strongly coordinated by the complexing agent, producing a stable and homogeneous solution. Since the concentration of free In^{3+} ions remains extremely low, premature precipitation is suppressed. As the bath temperature increases, the sulfur precursor undergoes hydrolysis, generating sulfide ions at a slow rate. Simultaneously, the indium complex gradually dissociates, releasing free In^{3+} ions into the solution. The controlled release of both ionic species is essential because it determines the degree of supersaturation and hence the nucleation rate. When the ionic product exceeds the solubility product of In_2S_3, nuclei begin to form on the substrate surface. This heterogeneous nucleation is thermodynamically favored because the substrate lowers the activation energy barrier compared with homogeneous nucleation in the bulk solution. Numerous nanosized nuclei form uniformly over the substrate surface, providing active sites for subsequent crystal growth. Once stable nuclei are formed, additional In^{3+} and S^{2-} ions diffuse toward these nuclei and become incorporated into the crystal lattice. Neighboring crystallites gradually grow and coalesce, eventually forming a continuous polycrystalline film. The final microstructure depends strongly on the deposition conditions. Two principal mechanisms contribute to film formation during CBD.

1) Ion-by-ion mechanism - In this mechanism, free In^{3+} and S^{2-} ions diffuse directly to the substrate surface and react there to form In_2S_3. The characteristics include smooth surface morphology, compact films, good adhesion, lower defect density, better stoichiometric control. Since crystal growth occurs atom by atom, films deposited through this mechanism generally exhibit superior optical and electrical properties.

2) Cluster-by-cluster mechanism- In this mechanism, In_2S_3 particles first nucleate within the solution and subsequently settle onto the substrate. This process generally produces rough surfaces, porous films, larger grains, poorer adhesion, increased scattering centers.

Most practical CBD processes involve contributions from both mechanisms. The relative contribution depends on bath supersaturation, pH, temperature, and precursor concentration. The structural, optical, electrical, and morphological properties of In_2S_3 thin films are highly sensitive to deposition conditions. The concentration of indium and sulfur precursors governs the supersaturation level of the bath. Low concentrations generally produce thin films with slow growth rates, whereas excessively high concentrations lead to homogeneous precipitation and poor adhesion. An optimum precursor concentration promotes uniform nucleation and compact film formation. Temperature significantly influences precursor hydrolysis, reaction kinetics, and crystal growth. At low temperatures, sulfide ion generation is slow, resulting in amorphous or poorly crystalline films. Increasing the bath temperature accelerates precursor decomposition and enhances atomic mobility, leading to larger grains and improved crystallinity. However, excessively high temperatures may cause rapid precipitation in the bulk solution and deteriorate film quality. CBD of In_2S_3 is commonly performed between 60 and 90 °C. The pH controls the stability of metal complexes and the concentration of sulfide ions. Acidic solutions suppress sulfide ion formation, resulting in slow deposition. Highly alkaline solutions promote rapid sulfide generation, increasing homogeneous precipitation. Therefore, moderately acidic to near-neutral conditions generally produce high-quality In_2S_3 films. The concentration of EDTA, TEA, or citrate determines the release rate of indium ions. Insufficient complexing agent leads to immediate precipitation. Excessive complexation slows deposition considerably. An optimized concentration ensures steady nucleation and continuous crystal growth. Film thickness increases approximately linearly during the early stages of deposition. Longer deposition times generally produce thicker films and larger grains. However, excessively long deposition may lead to peeling, cracking, or poor adhesion because of accumulated internal stress. Gentle magnetic stirring improves solution homogeneity, enhances mass transport, and prevents localized depletion of reactants near the substrate surface. Excessive stirring may disturb nucleation and promote unwanted particle formation in the solution. Post-deposition annealing plays a critical role in improving film quality. Annealing enhances crystallinity, grain growth, sulfur diffusion, defect reduction, electrical conductivity, optical transparency. Typical annealing temperatures range from 250 to 450 °C depending on the substrate and desired phase.

CBD possesses several advantages over vacuum deposition techniques. It include simple experimental setup requiring inexpensive equipment, low deposition temperatures compatible with heat-sensitive substrates, excellent coverage over large and irregularly shaped surfaces, scalability for industrial production, minimal energy consumption, ease of controlling film thickness through deposition time, suitability for multilayer device fabrication, low precursor consumption and reduced processing costs, compatibility with flexible substrates and transparent conducting oxides. Because of these advantages, CBD remains one of the most attractive techniques for producing In_2S_3 buffer layers in thin-film photovoltaic devices [8].

Despite its numerous advantages, CBD also has certain limitations. The deposition rate is relatively slow compared with vacuum techniques. Maintaining bath stability over long deposition periods can be challenging because precursor depletion alters the reaction kinetics. Homogeneous precipitation within the solution often competes with heterogeneous film growth, reducing precursor utilization and increasing material wastage. Films deposited at low temperatures generally exhibit moderate crystallinity and may require post-deposition annealing to improve structural quality. Residual impurities originating from complexing agents or incompletely decomposed sulfur precursors can remain incorporated within the films, influencing their electrical and optical properties. Furthermore, achieving precise stoichiometric control is more difficult than in sophisticated vacuum deposition methods.

3. Successive Ionic Layer Adsorption and Reaction (SILAR)

The SILAR process relies on four sequential steps that together constitute one deposition cycle. During each cycle, a very thin layer of the desired compound is formed on the substrate surface. Repetition of the cycle gradually increases the film thickness in a controlled manner. Unlike CBD, where the film grows continuously in a single solution, the SILAR technique separates the cation adsorption and anion reaction into independent steps. As a result, the growth process is governed primarily by surface reactions rather than precipitation in the bulk solution. The amount of material deposited during each cycle depends on the number of active adsorption sites available on the substrate surface. Once these sites are occupied, further adsorption does not occur until the next cycle. This self-limiting behavior provides excellent control over film thickness and composition. The deposition of In_2S_3 thin films by the SILAR method generally involves four successive stages.

i. Step 1: Adsorption of Indium Ions- The cleaned substrate is immersed in a cationic precursor solution containing In^{3+} ions, commonly prepared using indium chloride ($InCl_3$), indium nitrate [$In(NO_3)_3$], or indium sulfate [$In_2(SO_4)_3$]. During immersion, indium ions are adsorbed onto the substrate surface through electrostatic interactions or chemical bonding with available surface functional groups. Only a limited number of adsorption sites are available; therefore, the adsorption process is self-limiting and contributes to the excellent thickness control achieved by SILAR.

ii. Step 2: First Rinsing: After adsorption, the substrate is rinsed thoroughly with deionized water to remove weakly adsorbed or excess indium ions. This rinsing step serves several important functions like prevents homogeneous precipitation, removes loosely attached precursor molecules, avoids contamination of the sulfur precursor solution, improves film uniformity, enhances adhesion of the deposited layer. Without proper rinsing, direct mixing of cationic and anionic solutions would occur, leading to unwanted precipitation in the reaction vessel rather than on the substrate.

iii. Step 3: Adsorption of Sulfide Ions: The substrate is subsequently immersed in an anionic precursor solution containing sulfide ions. Common sulfur sources include sodium sulfide (Na_2S), thiourea, thioacetamide, sodium thiosulfate. The adsorbed indium ions react immediately with sulfide ions to form a thin layer of indium sulfide on the substrate surface. Because the reaction occurs only at the substrate surface, the deposited layer remains highly adherent and relatively uniform.

iv. Step 4: Final Rinsing- Following sulfide adsorption, the substrate is again rinsed with deionized water to remove excess sulfur ions and any loosely bound reaction products. This final rinsing step prevents contamination of the cationic precursor during the next deposition cycle and maintains the purity of the deposited film. After completion of the fourth step, one SILAR cycle is finished. Repetition of the cycle gradually increases the film thickness [9].

Film formation during the SILAR process proceeds through repeated adsorption and reaction events occurring exclusively on the substrate surface. Initially, isolated In_2S_3 nuclei are formed after the first few deposition cycles. These nuclei serve as active growth centers for subsequent cycles. As additional cycles are performed, the nuclei grow laterally and vertically through successive incorporation of indium and sulfur ions. Neighboring crystallites eventually coalesce to form a continuous polycrystalline film. Further cycling increases the thickness and promotes grain growth. Unlike CBD, where both ion-by-ion and cluster-by-cluster mechanisms may contribute simultaneously, SILAR growth is predominantly governed by sequential surface adsorption. Consequently, homogeneous precipitation is greatly reduced, resulting in better utilization of precursor materials. The final microstructure depends on several factors, including the adsorption time, precursor concentration, solution pH, and the total number of SILAR cycles.

The properties of In_2S_3 thin films synthesized by SILAR depend strongly on the deposition conditions. The concentration of indium and sulfur precursors determines the amount of ions adsorbed during each cycle. Low precursor concentrations generally produce thinner films with slower growth rates, whereas excessively high concentrations may cause particle agglomeration and non-uniform deposition. Optimized concentrations provide uniform coverage and controlled crystal growth. The number of deposition cycles is the most important parameter controlling film thickness. As the number of cycles increases, the film becomes thicker and grain size generally increases because of continued crystal growth. However, excessive cycling may generate internal stress, surface roughness, or microcracks within the deposited layer. The adsorption time in each precursor solution influences the amount of material deposited per cycle. Short immersion times may result in incomplete surface coverage, while excessively long times offer little additional benefit because adsorption becomes saturated once all available surface sites are occupied. Adequate rinsing removes excess precursor ions and prevents cross-contamination between the cationic and anionic solutions. Insufficient rinsing can lead to uncontrolled precipitation and poor film quality. The pH affects the stability of indium complexes as well as the concentration of sulfide ions available for reaction. Proper pH control is therefore essential for obtaining stoichiometric In_2S_3 films with improved crystallinity. Although SILAR can be performed at room temperature, moderate heating of the precursor solutions may enhance adsorption kinetics and improve crystallinity. Most reported In_2S_3 films are deposited between room temperature and approximately 70 °C. Annealing significantly improves crystallinity by promoting grain growth and reducing structural defects. It also removes residual hydroxides, improves stoichiometry, enhances optical transparency, and increases electrical conductivity. Annealing temperatures typically range from 250 to 450 °C, depending on the substrate and application.

The SILAR technique offers several advantages over many conventional thin-film deposition methods. Simple and inexpensive experimental setup, no requirement for vacuum systems or sophisticated instrumentation, deposition at room temperature or low temperatures, excellent control over film thickness through the number of deposition cycles, uniform coating on substrates of complex geometry, low precursor consumption, minimal chemical waste generation, high material utilization efficiency, easy control of film composition, suitable for large-area deposition, compatibility with glass, FTO, ITO, silicon, metal foils, and flexible polymer substrates, environmentally friendly because only small quantities of precursor solutions are used. These advantages make SILAR particularly attractive for large-scale production of semiconductor thin films intended for photovoltaic and photoelectrochemical applications.

Despite its advantages, SILAR also possesses certain limitations. The deposition rate is relatively slow because only a small amount of material is deposited during each cycle. Fabrication of thick films requires a large number of cycles, increasing the overall processing time. The repeated immersion and rinsing steps make the process labor-intensive unless automated equipment is employed. Film crystallinity obtained directly after deposition is generally moderate, necessitating post-deposition annealing for many applications. In addition, achieving highly stoichiometric films requires careful optimization of precursor concentrations, immersion times, and pH.

4. Spray Pyrolysis

Spray pyrolysis is based on the thermal decomposition of precursor compounds deposited from atomized liquid droplets. A homogeneous precursor solution containing indium and sulfur sources is converted into a fine aerosol using an atomizer or spray nozzle. The aerosol is carried by compressed air, nitrogen, oxygen, or another inert gas toward a substrate maintained at an elevated temperature. When the droplets impinge on the heated substrate, a series of physicochemical processes occur in rapid succession: Transport of droplets to the substrate, evaporation of the solvent, concentration of precursor species within the shrinking droplets, thermal decomposition of precursor compounds, chemical reaction between indium and sulfur species, nucleation of In_2S_3 crystals, crystal growth and coalescence, formation of a continuous polycrystalline thin film.

The precursor solution is typically prepared by dissolving the desired chemicals in deionized water, ethanol, methanol, or mixed solvents. Additives such as complexing agents, surfactants, or stabilizers may also be incorporated to improve solution stability and enhance film quality. The formation of In_2S_3 thin films by spray pyrolysis involves several sequential stages.

The precursor solution is atomized into droplets ranging from a few to several tens of micrometres in diameter. Smaller droplets generally produce smoother and denser films because they evaporate more rapidly and uniformly. The carrier gas transports the droplets toward the heated substrate. During transport, partial evaporation of the solvent reduces the droplet size and increases the concentration of precursor species. Upon contacting the heated substrate, rapid evaporation of the remaining solvent occurs. This process leaves behind concentrated precursor residues on the substrate surface. The precursor salts undergo thermal decomposition because of the high substrate temperature, producing reactive indium and sulfur species. Once sufficient concentrations of indium and sulfur species are available, In_2S_3 nuclei begin to form on the substrate surface. The number of nuclei formed depends strongly on substrate temperature and supersaturation. Additional precursor species diffuse toward the nuclei, resulting in grain growth. Neighboring crystallites gradually coalesce to produce a continuous polycrystalline thin film. The grain size and crystallinity depend on the deposition temperature, droplet size, precursor concentration, and deposition rate[9].

Several process parameters significantly influence the structural, optical, electrical, and morphological properties of In_2S_3 thin films. Substrate temperature is the most critical parameter in spray pyrolysis. It determines solvent evaporation, precursor decomposition, nucleation rate, and crystal growth. At low temperatures, solvent evaporation is incomplete, producing porous or poorly crystalline films. Increasing the substrate temperature enhances precursor decomposition and atomic diffusion, leading to improved crystallinity and larger grain sizes. However, excessively high temperatures may cause precursor decomposition before the droplets reach the substrate or lead to sulfur loss, resulting in non-stoichiometric films. Typical substrate temperatures for In_2S_3 deposition range from 250 to 450 °C. The spray rate determines the amount of precursor delivered to the substrate per unit time. A low spray rate allows sufficient time for solvent evaporation and thermal decomposition, producing compact films. Conversely, a high spray rate may cool the substrate surface, resulting in incomplete decomposition, poor adhesion, and rough morphology. The distance between the spray nozzle and substrate influences droplet evaporation and deposition efficiency. If the distance is too short, large droplets reach the substrate before sufficient solvent evaporation occurs, producing rough films. If the distance is too large, excessive evaporation may occur during transport, reducing deposition efficiency. An optimized nozzle-to-substrate distance provides uniform coverage and improved film quality. The carrier gas pressure determines the velocity and size distribution of the atomized droplets. Higher gas pressures generally produce finer droplets and more uniform coatings. However, excessive pressure may reduce deposition efficiency because many droplets are deflected away from the substrate. Compressed air and nitrogen are the most commonly used carrier gases. The concentration of precursor salts affects the deposition rate and film thickness. Low concentrations generally produce thinner films with slower growth rates. High concentrations increase film thickness but may also promote particle agglomeration and surface roughness. An optimized precursor concentration is therefore necessary to obtain dense and homogeneous In_2S_3 films. The precursor solution flow rate controls the quantity of solution supplied to the atomizer. A constant and well-controlled flow rate ensures uniform deposition throughout the process. Film thickness increases with deposition time. Initially, nucleation dominates the growth process, whereas prolonged deposition promotes grain growth and crystal coalescence. Excessively long deposition times may generate internal stresses, resulting in film cracking or peeling. Annealing considerably improves film quality by increasing crystallinity, reducing structural defects, removing residual impurities, and promoting grain growth. Annealing also enhances optical transparency and electrical conductivity while improving phase purity.

Spray pyrolysis offers numerous advantages for synthesizing In_2S_3 thin films. Simple and inexpensive experimental setup, no requirement for vacuum equipment, Suitable for large-area deposition, High deposition rate, easy control of precursor composition, excellent scalability for industrial production, uniform coating on substrates with complex geometries, ability to deposit multilayer structures, good reproducibility, low material and operating costs, compatibility with glass, FTO, ITO, silicon, ceramics, and metal substrates. Because of these advantages, spray pyrolysis is widely employed for manufacturing thin-film photovoltaic and optoelectronic devices.

Despite its advantages, spray pyrolysis has several limitations. The film quality is highly sensitive to process parameters, requiring careful optimization of substrate temperature, spray rate, carrier gas pressure, and nozzle-to-substrate distance. Poorly optimized conditions may produce rough surfaces, porous films, non-uniform thickness, or undesirable secondary phases. In addition, sulfur volatilization at high temperatures can lead to sulfur-deficient films, making post-deposition sulfurization or annealing necessary in some cases. Thickness uniformity over very large substrates may also be challenging without automated spray systems.

5. Electrodeposition

Electrodeposition is based on electrochemical reactions occurring at the electrode–electrolyte interface. When an appropriate electrical potential is applied between the working electrode and the counter electrode, ionic species present in the electrolyte undergo oxidation or reduction, leading to the formation of an insoluble semiconductor layer on the substrate surface. The electrolyte contains dissolved indium ions (In^{3+}) and sulfur-containing species. Under an applied cathodic potential, sulfur-containing compounds are electrochemically reduced to generate sulfide ions (S^{2-}), which subsequently react with indium ions near the electrode surface to form In_2S_3 [10].

Since the electrochemical reaction occurs only at the electrode surface, the deposited film is generally uniform, compact, and strongly adherent. Film thickness can be precisely controlled by adjusting the deposition time, applied potential, or total charge passed during the deposition process. A typical electrodeposition system consists of a three-electrode electrochemical cell comprising: Working electrode: conductive substrate (FTO, ITO, stainless steel, titanium, or metal foil) on which the In_2S_3 film is deposited. Counter electrode: inert material such as platinum or graphite, which completes the electrical circuit. Reference electrode: Ag/AgCl, saturated calomel electrode (SCE), or Hg/Hg_2SO_4, used to maintain an accurately controlled deposition potential. The electrolyte contains soluble indium salts and sulfur precursors dissolved in deionized water or suitable aqueous media. A potentiostat or galvanostat supplies the required electrical potential or current throughout the deposition process.

The composition of the electrolyte strongly influences the deposition kinetics, stoichiometry, and crystallinity of In_2S_3 thin films. Complexing agents such as citric acid, EDTA, sodium citrate, or triethanolamine are frequently added to stabilize In^{3+} ions and regulate the deposition rate. Supporting electrolytes, including sodium sulfate or potassium chloride, may also be incorporated to increase the electrical conductivity of the solution and improve current distribution.

The electrodeposition of In_2S_3 proceeds through several sequential stages. Indium ions and sulfur-containing species migrate through the electrolyte toward the cathode under the influence of diffusion, migration, and convection. At the cathode surface, sulfur precursor species undergo electrochemical reduction to generate sulfide ions. The applied potential controls the rate of this reaction and consequently influences the deposition rate. When sufficient concentrations of In^{3+} and S^{2-} ions are present near the electrode surface, stable In_2S_3 nuclei begin to form. Initially, numerous nanoscale nuclei are generated uniformly over the substrate. As deposition proceeds, additional ions diffuse toward the nuclei and become incorporated into the crystal lattice. Neighboring crystallites gradually coalesce, forming a continuous polycrystalline film. Grain size increases with deposition time and post-deposition heat treatment.

The growth mechanism generally follows a nucleation-and-growth model in which the density of nuclei and the subsequent grain growth are controlled by the applied potential and mass transport within the electrolyte.

Several electrochemical techniques have been employed for the deposition of In_2S_3 thin films. In potentiostatic deposition, a constant potential is applied throughout the deposition process. The current varies with time depending on nucleation and crystal growth. This method provides excellent control over film composition and thickness. In galvanostatic deposition, a constant current is maintained while the electrode potential changes automatically during deposition. This technique is widely used for large-area deposition because of its operational simplicity. In pulsed electrodeposition, alternating deposition and relaxation periods are applied. Pulsed operation improves ion diffusion, reduces concentration polarization, refines grain size, and produces smoother and denser films compared with continuous deposition.

The quality of electrodeposited In_2S_3 thin films depends strongly on several experimental parameters. The applied cathodic potential is one of the most important deposition parameters. At low potentials, the deposition rate is slow and thin films are produced. Increasing the potential accelerates nucleation and film growth. However, excessively negative potentials may promote hydrogen evolution and cause porous or poorly adherent films. The concentration of indium ions, sulfur precursor, and supporting electrolyte determines the deposition kinetics and final stoichiometry. Optimized electrolyte composition ensures uniform nucleation and minimizes the formation of secondary phases. The pH influences the stability of indium complexes and the availability of sulfur species. Highly acidic or highly alkaline electrolytes may decrease deposition efficiency or produce non-stoichiometric films. Therefore, careful pH adjustment is essential for obtaining high-quality In_2S_3 coatings. Current density directly affects the deposition rate and grain size. Low current densities generally produce compact and smooth films, whereas excessively high current densities may lead to rapid nucleation, coarse grains, surface roughness, and internal stress. Film thickness increases with deposition time. Initially, nucleation dominates the process, while prolonged deposition promotes crystal growth and grain coalescence. Excessively long deposition times may induce mechanical stress, resulting in cracking or peeling of the film. Although electrodeposition is generally performed at room temperature, moderate heating of the electrolyte can enhance ionic mobility, improve reaction kinetics, and promote better crystallinity. Magnetic stirring improves mass transport of ionic species toward the electrode surface, reduces concentration gradients, and produces films with better thickness uniformity. Excessive stirring, however, may disturb the diffusion layer and influence deposition kinetics. Freshly electrodeposited In_2S_3 thin films are often poorly crystalline or partially amorphous. Consequently, post-deposition annealing is commonly employed to improve structural and functional properties. Annealing promotes crystallization of amorphous regions, grain growth, reduction of structural defects, improvement in phase purity, enhancement of electrical conductivity, increase in carrier mobility, improvement of optical transparency, better adhesion between the film and substrate. Annealing is typically carried out in air, nitrogen, argon, sulfur, or hydrogen sulfide atmospheres at temperatures ranging from 250 to 500 °C, depending on the substrate and the intended application. Electrodeposition offers numerous advantages for synthesizing In_2S_3 thin films. It include simple and inexpensive equipment, low deposition temperature, excellent control over film thickness and deposition rate, high material utilization efficiency, low precursor consumption, uniform deposition on conductive substrates, strong adhesion between the film and substrate, easy control of stoichiometry through electrochemical parameters, scalable and suitable for industrial production, environmentally friendly due to minimal chemical waste, capability to deposit multilayer and nanostructured films. These advantages make electrodeposition particularly attractive for preparing semiconductor films for photovoltaic, electrochemical, and optoelectronic devices.

Despite its many advantages, electrodeposition has certain limitations. The process is restricted to electrically conductive substrates, limiting the direct deposition of films on insulating materials unless they are coated with a conductive layer. Precise control of the applied potential and electrolyte composition is essential to obtain stoichiometric In_2S_3 films. Competing side reactions, particularly hydrogen evolution at high cathodic potentials, can decrease deposition efficiency and produce porous coatings. Furthermore, as-deposited films often exhibit moderate crystallinity and therefore require post-deposition annealing to improve phase purity and electrical properties.

6. Challenges and Future Perspectives

Despite considerable progress, several challenges remain in the synthesis of In_2S_3 thin films. Achieving precise stoichiometric control, minimizing intrinsic defects, improving crystallinity at low temperatures, and scaling laboratory processes to industrial production continue to be active areas of research. Future efforts are expected to focus on environmentally benign precursor systems, rapid low-temperature deposition methods, roll-to-roll manufacturing, and the integration of In_2S_3 films into next-generation photovoltaic and optoelectronic devices.

References

1. Mishra, M., Kumar, S., Malik, S. B., Llobet, E., Güell, F., & John, T. T. (2025). Influence of substrate temperature on In_2S_3 thin films synthesized via two-step sulfurization for ultra-sensitive and selective NO_2 detection. *Sensors and Actuators B: Chemical*, *423*, Article 137819. https://doi.org/10.1016/j.snb.2025.137819
2. Yang, X., Chang, H., Graf, A., Li, X., Xia, Y., Tahir, A. A., & Zhu, Y. (2026). Photoelectrochemical stability enhancement of (311)-oriented indium sulfide thin films via In-cystine complex formation under hydrothermal synthesis. *ACS Applied Energy Materials*, *9*(4), 2131–2143. https://doi.org/10.1021/acsaem.5c03568
3. Funaki, A., Furumaki, F., Nishimura, T., & Yamada, A. (2024). In_2S_3 thin films via open-air chemical vapor deposition using indium-diethyldithiocarbamate: Deposition and characterization. *physica status solidi (RRL) – Rapid Research Letters*, *18*(4), Article 2300383. https://doi.org/10.1002/pssr.202300383
4. Benfraj, M., Souissi, R., Tiss, B., Ihzaz, N., Bouzidi, C., El Mir, L., & Bouguila, N. (2026). Investigation of structural and optoelectronic properties of indium sulfide thin films for

optoelectronic devices. *Journal of Materials Science: Materials in Electronics*, *37*, Article 684. https://doi.org/10.1007/s10854-026-17101-6

5. Chate, P. A., Sathe, D. J., Hankare, P. P., Lakade, S. D., & Bhabad, V. D. (2015). β-In_2S_3: Structural, optical, electrical and photoelectrochemical properties. *Optik*, *126*(24), 5715–5717. https://doi.org/10.1016/j.ijleo.2015.09.083
6. Chate, P. A., & Sathe, D. J. (2019). Chemical bath deposition technique for metal chalcogenides. In H. S. Min (Ed.), *Metal Chalcogenide Nanostructures: Characteristics and Synthesis* (pp. 32–52). OMICS International.
7. Gao, Z., Liu, J., & Wang, H. (2012). Investigation on growth of In_2S_3 thin films by chemical bath deposition. *Materials Science in Semiconductor Processing*, *15*(2), 187–193. https://doi.org/10.1016/j.mssp.2011.09.012
8. Chate, P. A., & Sathe, D. J. (2026). Deposition and characterization of metal chalcogenide thin films for optoelectronic applications (Chapter 11). In *Emerging Perspectives in Science and Technology Research* (Vol. 1, 1st ed.). Bhumi Publishing.
9. Ranjith, R., John, T. T., Kartha, C. S., Vijayakumar, K. P., Abe, T., & Kashiwaba, Y. (2007). Indium sulfide thin films deposited using SILAR technique. *Materials Science in Semiconductor Processing*, *10*(1), 49–54. https://doi.org/10.1016/j.mssp.2006.10.017
10. Marí, B., Mollar, M., Soro, D., Henríquez, R., Schrebler, R., & Gómez, H. (2013). Electrodeposition of In_2S_3 thin films onto FTO substrate from DMSO solution. *International Journal of Electrochemical Science*, *8*(3), 3510–3518.

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