

Engineering Materials

Arnold C. Alguno · Rey Y. Capangpangan ·
Gerard G. Dumancas ·
Arnold A. Lubguban ·
Roberto M. Malaluan ·
Rolen Brian P. Rivera

Metal Nanoparticles-Based Nanoplatforms for Colorimetric Sensing

Mechanisms, Applications, and Future
Directions



Springer

Engineering Materials

This series provides topical information on innovative, structural and functional materials and composites with applications in optical, electrical, mechanical, civil, aeronautical, medical, bio- and nano-engineering. The individual volumes are complete, comprehensive monographs covering the structure, properties, manufacturing process and applications of these materials. This multidisciplinary series is devoted to professionals, students and all those interested in the latest developments in the Materials Science field, that look for a carefully selected collection of high quality review articles on their respective field of expertise.

Indexed at Compendex (2021) and Scopus (2022)

Arnold C. Alguno · Rey Y. Capangpangan ·
Gerard G. Dumancas · Arnold A. Lubguban ·
Roberto M. Malaluan · Rolen Brian P. Rivera

Metal Nanoparticles-Based Nanoplatfoms for Colorimetric Sensing

Mechanisms, Applications, and Future
Directions

Arnold C. Alguno
Department of Materials and Resources
Engineering and Technology
Mindanao State University—Iligan Institute
of Technology
Iligan City, Philippines

Rey Y. Capangpangan
Department of Physical Sciences
and Mathematics, College of Marine
and Allied Sciences
Mindanao State University at Naawan
Naawan, Philippines

Gerard G. Dumancas
Honors College and the Department
of Chemistry
North Carolina Agricultural and Technical
State University
Greensboro, NC, USA

Arnold A. Lubguban
Department of Chemical Engineering
and Technology
Mindanao State University—Iligan Institute
of Technology
Iligan City, Philippines

Roberto M. Malaluan
Department of Chemical Engineering
and Technology
Mindanao State University—Iligan Institute
of Technology
Iligan City, Philippines

Rolen Brian P. Rivera
Mindanao State University—Iligan Institute
of Technology
Iligan City, Philippines

ISSN 1612-1317
Engineering Materials

ISSN 1868-1212 (electronic)

ISBN 978-981-96-6770-3

ISBN 978-981-96-6771-0 (eBook)

<https://doi.org/10.1007/978-981-96-6771-0>

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Singapore Pte Ltd. 2025

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd. The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

If disposing of this product, please recycle the paper.

Preface

The effectiveness of nanotechnology represents a paradigm shift in analytical chemistry, combining accuracy, simplicity, and high sensitivity as a solution to the greatest challenges in environmental monitoring, food safety, and medical diagnostics. This book, *Metal Nanoparticles-Based Nanoplatfoms for Colorimetric Sensing: Mechanisms, Applications, and Future Directions*, compiles pioneering research and innovation in this rapidly evolving field. This review highlights the excellent properties of metal nanoparticles (MNPs) such as gold, silver, and copper, in forming nanoplatfoms that exploit their optical and catalytic properties for highly sensitive colorimetric detection.

The effectiveness of metal nanoparticles is partly attributed to their ability to exhibit localized surface plasmon resonance, which produces visible color changes indicating molecular interactions in solution. This deceptively simple yet scientifically rich observation has led to rapid advances in the detection of a wide variety of analytes, from toxic heavy metals to clinically important biomarkers. By leveraging these properties, the research community has developed durable and easy-to-use sensing devices that enable real-time diagnostics on-site that would otherwise be difficult to achieve.

Theoretical concepts, experimental methodologies, and practical applications are consolidated in this book, making it a significant reference for scientists, engineers, and technologists. The chapters carefully examine the complex properties of metal nanoparticles, explore their cooperative effects in hybrid nanostructures, and address critical such as reproducibility, cost efficiency, and scalability. The book also discusses the future perspectives, including the integration of artificial intelligence and sustainable synthesis methods that are poised to reshape nanotechnology in the years ahead.

In tribute to this collaborative endeavor of scientific creativity, the current work encourages researchers to harness the capabilities of MNPs for colorimetric sensing, fostering innovations that promote sustainability, public health, and environmental

stewardship. Readers are invited to explore this dynamic field of nanoscience, where discovery meets application and challenges evolve into opportunities.

Iligan City, Philippines
Naawan, Philippines
Greensboro, North Carolina, USA
Iligan City, Philippines
Iligan City, Philippines
Iligan City, Philippines

Arnold C. Alguno
Rey Y. Capangpangan
Gerard G. Dumancas
Arnold A. Lubguban
Roberto M. Malaluan
Rolen Brian P. Rivera

Competing Interests The authors have no competing interests to declare that are relevant to the content of this manuscript.

Contents

1	Introduction to Metal Nanoparticle-Based Colorimetric Sensing	1
1.1	Overview of Colorimetric Sensing	1
1.1.1	Basic Principles and Historical Development of Colorimetric Detection	2
1.1.2	Visual-Based Detection Methods in Analytical Chemistry	3
1.2	The Role of Metal Nanoparticles in Colorimetric Platforms	3
1.2.1	Introduction to Colorimetric Sensing	5
1.2.2	The Role of Metal Nanoparticles in Colorimetric Platforms	6
1.3	Advantages of Metal Nanoparticle-Based Colorimetric Systems	7
1.3.1	Sensitivity, Selectivity, and Detection Limits	8
1.3.2	Practical Applications in Biosensing, Environmental Monitoring, and Food Safety	8
1.4	Objectives and Scope of the Book	9
1.4.1	Purpose of the Book in Consolidating Current Advancements	10
1.4.2	Outline of the Book Structure and Organization	10
	References	10
2	Gold Nanoparticle-Based Colorimetric Detection Systems	13
2.1	Properties of Gold Nanoparticles for Sensing	14
2.1.1	High Extinction Coefficient and Tunable Optical Properties	15
2.2	Mechanisms of Gold Nanoparticle-Based Colorimetric Reactions	16
2.2.1	Aggregation and Non-aggregation-Based Detection Strategies	17

2.2.2	Modifications and Functionalization for Enhanced Performance	17
2.3	Applications of Gold Nanoparticle-Based Sensors	19
2.3.1	Detection of Heavy Metals and Toxins	20
2.3.2	Medical Diagnostics: Cancer Markers, Proteins, and Nucleic Acids	20
2.3.3	Environmental Monitoring: Pesticide and Pollutant Detection	21
2.4	Challenges and Prospects	21
2.4.1	Overcoming Limitations in Stability, Reproducibility, and Sensitivity	22
	References	22
3	Copper Nanoparticles in Colorimetric Sensing	25
3.1	Unique Properties of Copper Nanoparticles	26
3.1.1	High Surface Area and Catalytic Activity	27
3.2	Mechanistic Insights into CuNPs-Based Colorimetric Reactions	27
3.2.1	Redox Reactions and Interaction with Various Analytes	28
3.2.2	Effect of Size and Surface Modifications on Detection Efficiency	28
3.3	Specific Applications of Copper Nanoparticle Sensors	29
3.3.1	Detection of Biomolecules	29
3.3.2	Monitoring of Environmental Pollutants	30
3.4	Challenges in the Use of Copper Nanoparticles	31
3.4.1	Issues Related to Oxidation, Stability, and Reproducibility	32
	References	32
4	Iron Nanoparticles for Colorimetric Sensing	37
4.1	Introduction to Iron Nanoparticles and Derivatives	37
4.1.1	Peroxidase-Like Activities of Fe ₃ O ₄ and Other Iron Oxides	39
4.2	Mechanisms of Iron-Based Colorimetric Platforms	39
4.2.1	Enzyme Mimicking Behaviors and Catalytic Pathways	40
4.3	Applications of Iron Nanoparticles	40
4.3.1	Detection of Hydrogen Peroxide, Glucose, and Other Small Molecules	41
4.3.2	Hybrid Systems with Fe-Based Metal Organic Frameworks (MOFs)	42
4.4	Challenges and Future Directions	43
4.4.1	Stability, Specificity, and New Avenues for Iron-Based Platforms	44
	References	44

5 Silver, Platinum, and Palladium Nanoparticles in Colorimetric Systems	47
5.1 Silver Nanoparticles (AgNPs)	48
5.1.1 Properties and Role in Aggregation-Based Sensing	48
5.1.2 Applications in Nucleic Acid and Protein Detection	50
5.2 Platinum Nanoparticles (PtNPs)	50
5.2.1 High Catalytic Activities and Signal Amplification	52
5.2.2 Detection of Environmental and Toxic Analytes	52
5.3 Palladium Nanoparticles (PdNPs)	53
5.3.1 Enzyme Mimicking Properties and Multi-target Detection	55
5.3.2 Integration in Advanced Biosensor Designs	56
5.4 Comparison and Complementary Use of Ag, Pt, and Pd Nanoparticles	56
5.4.1 Advantages and Limitations in Various Analytical Contexts	57
References	58
6 Hybrid and Composite Metal Nanoparticles for Colorimetric Sensing	61
6.1 Overview of Hybrid and Composite Nanostructures	61
6.1.1 Combining Multiple Metals and Functional Components	62
6.1.2 Design Strategies for Synergistic Enhancement	62
6.2 Hybrid Metal Nanoparticles for Colorimetric Platforms	63
6.2.1 Au@Fe ₃ O ₄ , Au@Pt, and DNA-Templated Ag/Pt Nanoclusters	63
6.3 Applications of Hybrid Nanoparticles	64
6.3.1 Multi-analyte Detection and Simultaneous Monitoring	64
6.3.2 Point-of-Care Diagnostics and Environmental Applications	65
6.4 Future Directions for Hybrid Nanomaterials	65
6.4.1 Developing Novel Structures with Superior Properties	66
6.4.2 Exploring New Functionalization Techniques	67
References	67
7 Applications of Metal Nanoparticles in Biosensing, Environmental Monitoring, and Medical Diagnostics	71
7.1 Metal Nanoparticles in Biosensing	71
7.1.1 Detection of DNA, RNA, Proteins, and Other Biomarkers	72
7.2 Environmental Monitoring Using Colorimetric Sensors	73
7.2.1 Detection of Heavy Metals, Pesticides, and Toxins in Water and Soil	74
7.3 Food Safety and Quality Control	75