



Functional Nanocomposites: From Strategic Design to Applications

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1. Introduction

Nanomaterials with one-, two-, or three-dimensional structures have exhibited superior optical, electronic, magnetic, thermal, and mechanical properties compared to their bulk material counterparts [1–5]. These unique properties have been extensively investigated for applications in various fields, such as light emission diodes (LEDs), solar cells, microchips, imaging agents, sensors, energy storage and conversion, and environmental protection [6–10]. These nanomaterials have also been widely employed as nanofillers in various polymer, ceramic, and metal matrices to fabricate advanced nanocomposites with enhanced and unique multifunctional properties [11–18]. The present Special Issue aims to further promote and expedite the research into high-performance nanocomposites to broaden their applications in a wide range of fields.

2. An Overview of Published Articles

Maier et al. reported the fabrication of cupric oxide nanowire (CuO NW) gas sensors on Si substrates and identified the optimum gap size, thickness, length, and width of Cu structures for efficient NW growth to bridge and electrically connect adjacent CuO structures [19]. For a film thickness of 560 nm, the best results were obtained by structures $4 \times 16 \mu\text{m}^2$ in size with a gap size of 3 μm . These optimal parameters were then evaluated and tested directly on a sensor chip, demonstrating a better sensing response to acetylene, ethane, ethene, and propene at ppm levels than to CO and CO₂.

Gence et al. reported the fabrication of conductive electrodes by integrating silver nanowires (AgNW) with titanium nitride (TiN) layers and then depositing them onto cellulose nanopaper and PET substrates using a low-temperature plasma-enhanced PLD technique, achieving thicknesses from 50 to 250 nm [20]. These TiN-AgNW nanocomposites demonstrated an improved electromechanical performance with minimal impact on their optical transparency and a higher stability compared to pure AgNW, TiN coatings, and ITO/PET substrates upon bending and exposure to ambient air, making them promising candidates for flexible bio-compatible electronic devices.

AlGhamdi et al. explored TiO₂ nanoparticle-reinforced denture bases fabricated with two types of vat photopolymerization 3D printing technologies: digital light processing (DLP) and stereolithography (SLA) [21]. The mechanical properties of the 3D-printed denture bases were found to be affected by the type of material used, the nanoparticle concentration, and the time after curing. For example, incorporating TiO₂ nanoparticles at concentrations of 1% and 2% was found to enhance flexural strength, while a 2% nanoparticle concentration resulted in a reduction in the elastic modulus and hardness of the 3D-printed nanocomposites. Their flexural strength and hardness also significantly improved with the increase in post-curing time. Gad et al. tested the effects of different denture cleansers on the color stability and surface roughness of 3D-printed denture base resins that were either unmodified or modified with ZrO₂ nanoparticle [22]. In this study, the authors recommended using Fittydent, Corega, and water as denture cleansers while



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advising against the use of NaOCl. AlGhamid et al. also found that the incorporation of ZrO₂ and SiO₂ nanoparticles into the 3D printed resins used for provisional restoration increased their hardness without affecting their surface roughness [23]. The use of SiO₂ resulted in only minor color changes, whereas ZrO₂ caused noticeable color alterations, exceeding perceptibility thresholds.

Oberhausen et al. fabricated self-healing magnetic polyelectrolyte nanocomposites using different concentrations of iron oxide nanoparticles [24]. The incorporation of these superparamagnetic nanoparticles into the polymer matrix facilitated spatially resolved healing under alternating magnetic fields due to the ionic interactions between the anionic copolymer and cationically functionalized iron oxide nanoparticles.

Bandaru et al. provided a comprehensive overview of the existing stimuli-independent and -dependent methodologies used to assemble nanomaterials, along with their desired structural and functional properties and the significance of their potential applications [25]. Some of the common stimuli-independent methods highlighted included solvent evaporation, gravitational sedimentation, and oriented attachment through covalent bonding, van der Waals forces, electrostatic interactions, and cation exchange. As for the stimuli-dependent methods, common triggers included light, electric fields, magnetic fields, temperature, solvents, acid bases, metal ions, biomacromolecules, and gases. Each approach offered distinct advantages tailored to specific applications, often resulting in organized structures with precisely controlled sizes, shapes, compositions, and properties.

In their review, Singh et al. highlighted the recent advances made in the development of polymeric composites with the use of boron nitride nanosheets (BNNs) and various filler alignment strategies during composite fabrication for the creation of high in-plane, cross-plane, and isotropic thermal conductive (TC) performances [26]. The significant challenges and major opportunities for the technological application of these nanocomposites were also identified and discussed. Several key characteristics have been identified as necessary to achieve high TC performances, including the use of thinner BNNs with larger lateral sizes, fewer defects, and high crystallinity, and their effective alignment, dispersibility, and interfacial compatibility within the polymer matrix.

3. Conclusions

In conclusion, this Special Issue is a collection of eight articles (six original research articles and two review articles) focused on advancing the development of functional nanocomposites for novel applications. Researchers have fabricated and characterized diverse functional nanocomposites by successfully integrating nanomaterials with zero-, one-, and two-dimensional structures into different matrix materials, enabling the creation of unique structures with precisely controlled sizes, shapes, and compositions and the realization of desired functionalities and tailored properties for various applications. The targeted applications discussed in this collection include self-healing, reinforced denture bases and cleansers, gas sensor chips, conductive bio-compatible flexible electronic devices, thermal management in modern electronic devices, and others. Our Special Issue will significantly contribute to and advance the research being conducted on high-performance functional nanocomposites and lead to applications that will appeal to a broad audience within the field of nanoscience and nanotechnology.

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References

1. Rohuner, E. Size Matters: Why Nanomaterials are Different. *Chem. Soc. Rev.* **2006**, *35*, 583. [[CrossRef](#)] [[PubMed](#)]
2. Cao, L.; Sahu, S.; Anilkumar, P.; Kong, C.Y.; Sun, Y.-P. Linear and Nonlinear Optical Properties of Modified Graphene-based Materials. *MRS Bull.* **2012**, *37*, 1283. [[CrossRef](#)]
3. Cao, L.; Meziani, M.J.; Sahu, S.; Sun, Y.-P. "Photoluminescence Properties of Graphene versus Other Carbon Nanomaterials". *Acc. Chem. Res.* **2013**, *46*, 171. [[CrossRef](#)] [[PubMed](#)]
4. Saleh, T.A. Nanomaterials: Classification, Properties, and Environmental Toxicities. *Environ. Technol. Innov.* **2020**, *20*, 101067. [[CrossRef](#)]
5. Baig, N.; Kammakakam, I.; Falath, W. Nanomaterials: A Review of Synthesis Methods, Properties, Recent Progress, and Challenges. *Mater. Adv.* **2021**, *2*, 1821. [[CrossRef](#)]
6. Chen, G.; Seo, J.; Yang, C.; Prasad, P.N. Nanochemistry and Nanomaterials for Photovoltaics. *Chem. Soc. Rev.* **2013**, *42*, 8304. [[CrossRef](#)]
7. Cao, L.; Fernando, K.A.S.; Liang, W.; Seilkop, A.; Veca, L.M.; Sun, Y.-P.; Bunker, C. Carbon Dots for Energy Conversion Applications. *J. Appl. Phys.* **2019**, *125*, 220903. [[CrossRef](#)]
8. Kolahalam, L.A.; Viswanath, I.V.K.; Diwakar, B.S.; Govindh, B.; Reddy, V.; Murthy, Y.L.N. Review on Nanomaterials: Synthesis and Applications. *Mater. Today Proc.* **2019**, *18*, 2182. [[CrossRef](#)]
9. El-Kady, M.M.; Ansari, I.; Arora, C.; Rai, N.; Soni, S.; Verma, D.K.; Singh, P.; Mahmoud, A.E.D. Nanomaterials: A Comprehensive Review of Applications, Toxicity, Impact, and Fate to Environment. *J. Mol. Liq.* **2023**, *370*, 121046. [[CrossRef](#)]
10. Hossain, N.; Mobarak, M.H.; Mimona, M.A.; Islam, M.A.; Hossain, A.; Zohura, F.T.; Chowdhury, M.A. Advances and Significances of Nanoparticles in Semiconductor Applications—A Review. *Results Eng.* **2023**, *19*, 101347. [[CrossRef](#)]
11. Minelli, C.; Lowe, S.B.; Stevens, M.M. Engineering Nanocomposite Materials for Cancer Therapy. *Small* **2010**, *6*, 2336. [[CrossRef](#)] [[PubMed](#)]
12. Meziani, M.J.; Song, W.L.; Wang, P.; Lu, F.; Hou, Z.; Anderson, A.; Maimaiti, H.; Sun, Y.-P. Boron Nitride Nanomaterials for Thermal Management Applications. *ChemPhysChem* **2015**, *16*, 1339. [[CrossRef](#)] [[PubMed](#)]
13. Siochi, E.; Harrison, J.S. Structural Nanocomposites for Aerospace Applications. *MRS Bull.* **2015**, *40*, 829. [[CrossRef](#)]
14. Omanović-Miklićanin, E.; Badnjević, A.; Kazlagić, A.; Hajlovac, M. Nanocomposites: A Brief Review. *Health Technol.* **2020**, *10*, 51. [[CrossRef](#)]
15. Hassan, T.; Salam, A.; Khan, A.; Khan, S.U.; Khanzada, H.; Wasim, M.; Khan, M.Q.; Kim, I.S. Functional Nanocomposites and Their Potential Applications: A Review. *J. Polym. Res.* **2021**, *28*, 36. [[CrossRef](#)]
16. Qadir, A.; Le, T.K.; Malik, M.; Min-Dianey, K.A.A.; Saeed, I.; Yu, Y.; Choi, J.R.; Pham, P.V. Representative 2D-material-based Nanocomposites and Their Emerging Applications: A Review. *RSC Adv.* **2021**, *11*, 23860. [[CrossRef](#)]
17. Cao, L.; Bradford-Vialva, R.L.; Eckerle, R.M.; Herman, F.; Jones, C.; Klosterman, D. Development of Carbon Nanotube-Reinforced Nickel-Based Nanocomposites Using Laser Powder Bed Fusion. *Adv. Eng. Mater.* **2023**, *25*, 2201197. [[CrossRef](#)]
18. Anwer, A.H.; Ahtesham, A.; Shoeb, M.; Mashkoor, F.; Ansari, M.Z.; Zhu, S.; Jeong, C. State-of-the-art Advances in Nanocomposite and Bio-nanocomposite Polymeric Materials: A Comprehensive Review. *Adv. Colloid Interface Sci.* **2023**, *318*, 102955. [[CrossRef](#)]
19. Maier, C.; Leitgeb, V.; Egger, L.; Köck, A. Size-dependent Thresholds in CuO Nanowires: Investigation of Growth from Microstructured Thin Films for Gas Sensing. *Nanomaterials* **2024**, *14*, 1207. [[CrossRef](#)]
20. Gence, L.; Quero, F.; Escalona, M.; Wheatley, R.; Seifert, B.; Diaz-Droguett, D.; Retamal, M.J.; Wallentowitz, S.; Volkmann, U.G.; Bhuyan, H. Wrinkled TiNAgNW Nanocomposites for High-Performance Flexible Electrodes on TEMPO-Oxidized Nanocellulose. *Nanomaterials* **2024**, *14*, 1178. [[CrossRef](#)]
21. AlGhamdi, M.A.; Fouda, S.M.; Taymour, N.; Akhtar, S.; Khan, S.Q.; Ali, M.S.; Elakel, A.M.; Nassar, E.A.; Gad, M.M. Comparative Evaluation of TiO₂ Nanoparticle Addition and Postcuring Time on the Flexural Properties and Hardness of Additively Fabricated Denture Base Resins. *Nanomaterials* **2023**, *13*, 3061. [[CrossRef](#)] [[PubMed](#)]
22. Gad, M.M.; Khattar, A.; Alramadan, D.M.; Al Dawood, Z.H.; Al Shehab, S.S.; Al Zaher, R.H.; Alzain, L.O.; Khan, S.Q.; Abdelfattah, M.Y. Nanoparticle-Modified 3D-Printed Denture Base Resins: Influence of Denture Cleansers on the Color Stability and Surface Roughness In Vitro. *Nanomaterials* **2024**, *14*, 891. [[CrossRef](#)] [[PubMed](#)]
23. AlGhamdi, M.A.; Alatiyyah, F.M.; Almedarham, R.F.; Al Dawood, Z.H.; Alshaikhnasser, F.Y.; Alboryh, S.Y.; Khan, S.Q.; Abualsaud, R.; Gad, M.M. Impact of Nanoparticle Addition on the Surface and Color Properties of Three-Dimensional (3D) Printed Polymer-Based Provisional Restorations. *Nanomaterials* **2024**, *14*, 665. [[CrossRef](#)] [[PubMed](#)]
24. Oberhausen, B.; Plohl, A.; Niebuur, B.-J.; Diebels, S.; Jung, A.; Kraus, T.; Kickelbick, G. Self-Healing Iron Oxide Polyelectrolyte Nanocomposites: Influence of Particle Agglomeration and Water on Mechanical Properties. *Nanomaterials* **2023**, *13*, 2983. [[CrossRef](#)] [[PubMed](#)]

25. Bandaru, S.; Arora, D.; Ganesh, K.M.; Umrao, S.; Thomas, S.; Bhaskar, S.; Chakraborty, S. Recent Advances in Research from Nanoparticle to Nano-Assembly: A Review. *Nanomaterials* **2024**, *14*, 1387. [[CrossRef](#)]
26. Singh, B.; Han, J.; Meziani, M.J.; Cao, L.; Yerra, S.; Collins, J.; Dumra, S.; Sun, Y.-P. Polymeric Nanocomposites of Boron Nitride Nanosheets for Enhanced Directional or Isotropic Thermal Transport Performance. *Nanomaterials* **2024**, *14*, 1259. [[CrossRef](#)]

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