Different Aspects of Metal Nanoclusters with Their Challenges and Future Perspectives

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Abstract
Nanoclusters, comprising aggregates of a few to several hundred metal atoms, have garnered significant attention due to their unique properties that bridge the gap between individual atoms and bulk materials. These nanoclusters exhibit distinct electronic, optical, and chemical characteristics, making them promising candidates for various applications in catalysis, biomedicine, and sensing. The present review article shows a glimpse on Nanoclusters.

Keywords: Nanoclusters, Quantum Confinement Effects, Catalysis, Biomedicine, Synthesis Techniques

1. Introduction
Nanoclusters are ultra-small particles, typically less than 2 nm in size, consisting of a precise number of atoms. They are ultra-small nanoparticles typically ranging from sub-nanometre to a few nanometres in size. They bridge the gap between atomic and nanoparticle scales, exhibiting unique physical, chemical, and electronic properties due to quantum confinement effects, large surface-to-volume ratios, and discrete electronic states (Jiang & Dai, 2021) [6]. Their properties differ markedly from larger nanoparticles due to quantum confinement effects, leading to discrete electronic states and size-dependent fluorescence. The ability to control their size and composition with atomic precision allows for the fine-tuning of their properties for specific applications. These properties make nanoclusters promising materials in diverse fields such as catalysis, biomedical applications, electronics, and sensing (Zhang *et al*, 2022) [21].

2. Synthesis of Nanoclusters
Nanoclusters can be synthesized through various methods, broadly categorized into physical, chemical, and biological approaches. Physical methods, including laser ablation and sputtering, offer high purity but may lack precise size control (Li & Kim, 2020) [9]. Chemical methods, such as wet chemical reduction, are widely used due to their scalability and ability to control the size and composition of nanoclusters through ligand protection and templating techniques (Wang *et al*, 2023) [17]. Biological methods utilize biomolecules and microorganisms to produce environmentally friendly nanoclusters (Chen & Gupta, 2021) [1].

3. Structure of Nanoclusters
Nanoclusters are aggregates of atoms that exhibit unique structural characteristics due to their small size, typically ranging from a few to a few hundred atoms. Their structure significantly influences their physical, chemical, and electronic properties, distinguishing them from bulk materials and larger nanoparticles (Zhang *et al*, 2020) [2].

3.1 Atomic arrangement and morphology
Nanoclusters can adopt various structural motifs depending on the type of atoms, synthesis methods, and environmental conditions. Common structural configurations include:

- **Face- Cantered Cubic (FCC) Structures:** Many metal nanoclusters, such as gold and silver, exhibit FCC packing similar to their bulk counterparts. However, due to the reduced size, nanoclusters often adopt high-symmetry geometries like icosahedral or decahedral shapes to minimize surface energy (Wang & Li, 2021) [18].

- **Icosahedral and decahedral structures:** These structures are more common in smaller clusters, providing a compromise between stability and surface energy. They often arise due to the dominance of surface atoms in nanoclusters (Li *et al*, 2022) [11].
- **Core-shell structures:** In bimetallic nanoclusters, a core-shell structure may form where one metal constitutes the core, and another forms the shell. This structure is particularly useful for tuning the catalytic and optical properties of the nanoclusters (Gupta & Singh, 2019) [5].

3.2 Ligand-protected nanoclusters
Nanoclusters often require stabilization to prevent aggregation. Ligands, such as thiols, phosphines, or polymers, bind to the surface atoms, offering steric or electrostatic stabilization (Zhu & Chen, 2023) [23]. The ligand-shell not only stabilizes the nanocluster but also influences its electronic structure and reactivity (Mukherjee *et al*, 2021) [13].

3.3. Electronic Structure
The electronic structure of nanoclusters is governed by quantum confinement effects. Unlike bulk materials with continuous electronic bands, nanoclusters exhibit discrete energy levels, similar to molecules (Chen *et al*, 2020) [2]. This leads to size-dependent optical and electronic properties, making nanoclusters particularly attractive for applications in photonics and catalysis (Yuan & Zhao, 2021) [20].

3.4. Surface structure and reactivity
The high surface-to-volume ratio in nanoclusters results in a large proportion of surface atoms with unsaturated coordination sites. This unique surface structure enhances the chemical reactivity of nanoclusters, particularly in catalytic applications (Das *et al*, 2022) [3]. The specific arrangement of atoms on the surface, including facets, edges, and corners, significantly affects the catalytic performance of the nanoclusters (Liu & Wang, 2023) [12].

4. Properties of Nanoclusters
Nanoclusters exhibit unique properties distinct from their bulk counterparts:
Nanoclusters exhibit distinctive optical, electronic, and catalytic properties. The optical properties of metal nanoclusters, for instance, are characterized by photoluminescence, which is highly tunable based on the size and composition of the clusters (Smith *et al*, 2020) [16]. Electronic properties include discrete energy levels and size-dependent band gaps, which are crucial for applications in optoelectronics (Lee & Tan, 2022) [8]. Catalytic properties arise from their high surface energy and active sites, enhancing performance in catalytic reactions (Patel & Singh, 2021) [15].

5. Applications of Nanoclusters
The unique properties of nanoclusters have led to their exploration in various fields:
- **Catalysis:** Due to their high surface-to-volume ratio, nanoclusters serve as effective catalysts in chemical reactions, including hydrogenation, oxidation, and electrocatalysis (Zhao *et al*, 2023) [22].
- **Biomedical Applications:** Nanoclusters are used in bioimaging, drug delivery, and therapeutic applications due to their biocompatibility and luminescent properties (Xu & Lin, 2021) [19].
- **Electronics:** The quantum confinement effect in nanoclusters is exploited in electronic devices, including transistors and sensors (Nguyen & Park, 2022) [14].
- **Sensing:** Nanoclusters' sensitivity to environmental changes makes them ideal for chemical and biological sensors (Ghosh *et al*, 2020) [4].

6. Challenges and future perspectives
Despite the promising applications, several challenges persist:
- **Stability**: Nanoclusters can be prone to aggregation, leading to loss of their unique properties. Developing robust synthesis methods and surface modifications to enhance stability is crucial.
- **Scalability**: Producing nanoclusters with consistent quality on a large scale remains a challenge. Advancements in synthesis techniques are needed to facilitate commercial applications.
- **Understanding Mechanisms**: A deeper understanding of the interaction mechanisms between nanoclusters and biological systems is essential to fully harness their potential in biomedicine. Despite their potential, nanoclusters face challenges related to stability, scalability of synthesis, and integration into practical devices (Li *et al*, 2023) [10]. Future research could focus on enhancing stability through surface modification and exploring new applications in emerging technologies (Kim & Zhou, 2024) [6].

7. Conclusion
Nanoclusters represent a fascinating class of nanomaterials with unique properties that are advantageous for a wide range of applications. Ongoing research aimed at addressing current challenges is expected to unlock their full potential, leading to significant advancements in technology and medicine. Advances in synthesis techniques and deeper understanding of their properties will likely drive further innovations in nanotechnology.

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