International Journal of Scientific Research in Physics and Applied Sciences
Vol.**13**, Issue.**2**, pp.**51-60**, April **2025**
E-ISSN: 2348-3423
Available online at: www.isroset.org

Review Article

A Brief Review of Magnetic, Transport, and Surface Properties of Smart Nanomaterials

Om Prakash Hota[1], Ananya Jena[2], S.K. Parida[3*]

[1,2,3]Dept. of Physics, ITER, Siksha O Anusandhan Deemed to be University, Bhubaneswar-751030, India

*Corresponding Author:

Received: 09/Feb/2025; **Accepted**: 11/Mar/2025; **Published**: 30/Apr/2025

Abstract— Smart nanomaterials have emerged as a pivotal class of materials due to their unique and tunable properties making them ideal candidates for advanced technological applications. This review focuses on the magnetic, transport, and surface properties of these materials, which play a crucial role in their functionality across diverse fields. The discussion begins with an overview of magnetic properties, highlighting the role of size, morphology, and composition in tailoring magnetism for applications such as data storage, biomedical imaging, and drug delivery. Next, the transport properties, including electrical and thermal conductivity are analyzed with emphasis on the mechanisms driving charge transport and their implications for electronic devices, sensors, and energy storage systems. The surface properties, including surface reactivity, wettability, and functionalization potential, are also explored, demonstrating their importance in catalysis, environmental remediation, and biomedical interfaces. A comprehensive analysis of recent advances, experimental techniques, and theoretical frameworks is provided to connect these properties to practical applications. Finally, the review identifies current challenges and prospects in the development of smart nanomaterials, emphasizing their role in next-generation technologies.

Keywords— Smart nanomaterials; surface properties; thermal conductivity; surface reactivity; experimental techniques

1. Introduction

Nanomaterials are defined as functional compounds with at least one dimension between 1 and 100 nm and a specific surface area by volume greater than 60 square centimeters/cubic centimeter. Because the surface-to-volume ratio is large in nanomaterial, people from different fields pay more attention to this material. Nanomaterials may differ from similar materials by not having nanoscale properties. From this, new chemical and physical characteristics, such as improved solubility, can be gained by changing optical behavior increased catalytic activity can occur and nanomaterials are released from man-made and natural sources into the environment through wildfires, sandstorms, lightning strikes, and volcanic eruptions which are examples of natural sources and mining friction, incineration, and nanotechnology are examples of anthropological causes [1-3]. Nanomaterials can also pose a health hazard to the environment. In addition to the technical and commercial benefits nanoparticles are now being used to produce transparent sunscreens, stain-proof clothing, self-cleaning windows, wall protective coating walls, anti-scratch glasses, unbreakable color, and ceramic coatings for solar cells, acts as an immunotherapy stimulant in diagnostic test and more than that, nanoparticles are becoming the building blocks of drugs [4-5]. These particles can penetrate tissue and target specific areas because of their small size, which is about the thickness of a DNA strand. When a material is created at the nanoscale, roughly less than 100 nm, it is called nanomaterial, but those materials respond uniquely and intelligently to many environmental stimuli, including temperature, light, pH, electric fields and chemical agents called smart nanomaterials [6-9]. The reason these materials are called "smart" is that they will dynamically alternate their houses in response to outdoor stimuli and revert to their authentic kingdom when the stimulus is removed. Their versatility renders them positive in numerous domains like environmental studies, strength, healthcare, and nanotechnology.

1.1 Historical Background

1.1.1 Metal

Since the prehistoric years, metals have been available and utilized for human welfare and manifestation. For copper metal, the first sign was about 9000 BC by the ancient book. The bronze medals, approximately 3500 BC, marked the first stage of the Bronze Age, an era during which tool-making, warfare armaments, and constructions in the early civilizations evolved exponentially. Its malleable, ductile, conductive nature of metals facilitated more diverse use. It has accelerated the usage of metals; hence, it paved the way for developments in engineering and manufacturing, even up to the present, because of its strength and ability to conduct electricity in buildings, transportation, and electronics [10].

1.1.2 Ceramics (3000 BC- 20th Century)
Ceramics have been used since ancient times, mostly for the production of ceramics and structures. The earliest known potters were manufactured nearly 29,000 years ago as ornamentation and utility pieces. Till 3000 years ago, advancements in firing technology resulted in high-grade quality ceramics for building and art purposes. Recently, the quality of the ceramics was improved with advanced mechanical and thermal properties. The enhanced ceramics are found to be widely used in aerospace, electronics, and biomedical fields [11].

1.1.3 Ceramic Composites (1960s - Present)
Ceramic composites came in the 1960s as a direct response to the demand for materials that brought out some of the attractive features associated with ceramics and other related materials. The composites exhibited enhanced toughness and thermal stability, which presented a high-performance potential application in the aerospace, automotive, and energy industries. The ability to incorporate fibers or particles within ceramic matrices has produced materials that can survive harsh temperatures, thereby increasing their applicability [12].

1.1.4 Nanomaterials (1980s - Present)
Research on nanomaterials began as early as the 1980s; it was realized that at the nanoscale, materials exhibit special properties that differ considerably from their bulk counterparts. Nanomaterials; carbon nanotubes and nanoparticles have been in use in fields such as electronics, medicine, and remediation of harmful environmental toxins; large surface areas to large volumes enhance reactivity and strengthen, making these nanosized materials critical to innovative technological developments [13].

1.1.5 Smart Nanomaterials (2000s - Present)
It can be said that the debut of smart nanomaterials in the year 2000 was the highest-ever milestone in materials research. Such materials can answer all external stimuli like temperature, pH or light, hence adjusting their characteristics in real-time. Such nanomaterials find applications in systems designed to deliver medication, in sensors and in adaptive optics, showing the power to change a range of sectors. Their capability of allowing functionality to be embedded within nanoscale structures opens options for innovation in technology and medicine [14].

1.2 Types of nanomaterials
Nanomaterials have special qualities at the nanoscale and are categorized according to their composition, structure, and place of origin. The main categories are as follows:
These consist of graphene, fullerenes, carbon nanotubes, nanodiamonds, and carbon quantum dots, amongst other kinds. Due to their well-known electric, mechanical, and thermal traits, these substances are crucial for a load of programs, including remedy transport, power garages, and environmental applications [15]. Metal nanoparticles, including those of gold, silver, platinum, and iron oxide, have gained attention due to their use in biological, sensing, and catalytic applications. By adjusting their size, shape, and surface functionalization, their special optical, magnetic, and chemical characteristics may be tuned.

1.2.1 Organic-nanomaterials
Drug delivery procedures commonly include organic nanoparticles, such as liposomes, dendrimers, and polymeric micelles, which may contain medicinal chemicals. These materials consist of organic molecules such as proteins, lipids, and polymers.

1.2.2 Inorganic -Nanomaterials:
This category includes ceramics and metal oxides (such as zinc and titanium oxide), which are prized for their thermal stability, magnetic qualities, and uses in photocatalysis, electronics, and environmental clean-up [16].

1.2.3 Composite Nanomaterials:
These materials are hybrids, combining several types of nanoparticles (such as metal-based and carbon-based nanoparticles). In technical and environmental applications, they are utilized to improve advanced materials' mechanical strength, thermal resistance, and conductivity These divisions demonstrate how adaptable nanoparticles are to problems in a variety of fields, such as electronics, environmental research, and medicine. Therefore, one of the main areas of research in substance technological know-how and nanoscience is the category of nanomaterials consistent with their structural dimensionality. The dimensions of nanomaterials are usually used to classify them based totally on how they behave physically, chemically, and electrically.

1.2.4 Zero-dimensional (0D) nanomaterials;
These materials are limited to the nanoscale in all three dimensions, usually resulting in particles or clusters [17]. The examples of zero dimensional nanomaterials are - Quantum dots are semiconductor nanoparticles that modify in size in terms of their optical and electric traits. Fullerenes are carbon atoms prepared in a round, ellipsoidal or cylindrical shape as molecules.

1.2.5 One-Dimensional (1D) nanomaterials:
These materials have one confinement dimension and two vast length dimensions. They often exhibit unique optical and electrical properties due to their elongated form [18]. The example of the 1D nanomaterials are - nanowires are systems with lengths up to numerous micro-meters & a diameter in the nanometer variety and carbon nanotubes.

1.2.6 Two-Dimensional (2D) Nanomaterials:
These substances have dimensions constrained to the nanoscale, with the third measurement spreading over more

scales. Because of their low dimension, they regularly display one-of-a-kind traits [19]. An example of 2D nanomaterials is graphene, which is crafted from just one sheet of carbon atoms organized in a hexagonal lattice and is well-diagnosed for possessing extremely good mechanical and electric properties. Transition steel dichalcogenides (TMDs): MoS_2 is one of the layered substances that may exfoliate into monolayers [20].

1.2.7 Three-dimensional (3D) nanoparticle materials;
Even though these materials' three dimensions all grow to the nanoscale, their shapes may be less uniform and more complex than those of 0D, 1D, or 2D substances. An example of 3D nanomaterials is nanostructured skinny films are longer and wider than nanoscale in thickness. Materials containing nanoparticles in a matrix that have been given improved traits through the nano-fibers are referred to as nanocomposites [21]. Therefore, the dimensionality-based categorization of nanomaterials is protected in elements in those works. The characteristics and use of every class of nanomaterials 0D, 1D, 2D, and 3D vary, and in addition, looking at them is needed to in addition our comprehension and utilization of these materials.

2. Literature Review

Studies on smart nanomaterials have accelerated because of exceptional magnetic, transport, and surface properties that increase innovation across various fields within science and industry. This has been a generally well-researched area of study, the behavior of nanomaterials at the nanoscale, where quantum effects, surface properties, and size confinements are responsible for unique properties compared to bulk materials. The earlier works of B. Viswanathan [1] and J.Z. Zhang [2] showed the basics of nanomaterials indicating that a reduction of the size of a particle would produce improvements in chemical reactivity, mechanical properties, and optical properties, which serves as a basis to look into the use of smart nanomaterials, or materials that illustrate responsive behaviors to external stimuli such as temperature, pH, magnetic fields and light. One aspect that has developed significantly in terms of magnetic properties is the creation of magnetic nanoparticles (MNPs) and their applications. Saima Gul et al. [23] and Magdalena Aflori [24] have shown that Superparamagnetism in nanoparticles such as Fe_3O_4 has potential applications in biomedical imaging, hyperthermia, and targeted drug delivery. Studies on ferrimagnetism and exchange bias effects in core-shell nanoparticles were also pursued and provided discussions about high-density magnetic storage and spintronic devices [27]-[31]. The transport properties of smart nanomaterials have also received considerable attention. For example, McEuen et al. [51] studied the ballistic transport in carbon nanotubes, while Huard et al. [49] looked at the influence of metal-graphene contacts on electron-hole asymmetry, which has implications for nanoscale electronic devices. Hochbaum et al. [52] provided a fundamental discussion about thermal transport, and their findings indicated that surface roughness in silicon nanowires could have a significant impact on thermoelectric performance through reduced phonon thermal conductivity. Surface properties, certainly the most prominent feature of nanomaterials, have also received considerable attention because of their role in catalysis, sensing, and biomedical applications. Song et al. [56] provided details on advanced surface functionalization techniques, enabling smart nanomaterials to act as sensors, drug carriers, and catalytic agents simultaneously. The surface area-to-volume ratio of nanomaterials enhances interactions with the environment and given the increased level of surface modification research, it is clear that more emphasis will be placed on the interaction of smart nanomaterials with the environment in the future. Recently, advances have taken place that combine these three areas (magnetic, transport, and surface properties) to create multifunctional smart nanomaterials for integrated applications. For example, magnetic nanoparticles with engineered surfaces can now display both improved conductivity and directed biological responses at the same time, which represents extremely promising avenues for new nanoelectronics, energy capture and storage, and personalized medicine [71]. In summary, in examining the literature it is clear that smart nanomaterials have been increasingly explored as a novel class of nanomaterials with unprecedented properties; however, significant challenges remain, including production scalability, environmental considerations of various production methods, and control over nanostructure functionality. Overall, these challenges provide ample opportunities for future research.

3. Smart nanomaterials

When a material is created at the nanoscale roughly less than 100 nanometers, it is referred to as a smart nanomaterial. These materials respond uniquely and intelligently to many environmental stimuli, including temperature, light, pH, electric fields, and chemical agents. The motive these materials are called "smart" is that they will dynamically alternate their houses in response to outdoor stimuli and revert to their authentic kingdom when the stimulus is removed. Their versatility renders them positive in numerous domain names, along with environmental studies, strength, healthcare, and nanotechnology. Here, we want to discuss the characteristics of smart nanomaterials and their importance in different fields of science of technology.
Nanoscale length: The substances own a great surface-region-to-quantity ratio because of their nanoscale size, that may improve their reactivity and ability to interact with external stimuli [22].
Response: They are capable of react right away to a whole lot of stimuli, consisting of versions in pH, mild, warmth, or magnetic fields.
Reversibility: These materials can often return to their original state once the stimulus is removed, indicating that their response to stimuli is reversible.
Versatility: These materials may be designed to perform numerous responsibilities primarily based on the meant use or the encircling situations.

4. Magnetic Properties

In many innovative applications, the magnetic characteristics of smart nanomaterials in particular, magnetic nanoparticles or MNPs are essential. Because of their nanoscale size, these nanoparticles, mostly made of iron oxides (such as Fe_3O_4), display unique magnetic characteristics, including superparamagnetic. As subjected to an external magnetic field, the particles in superparamagnetic materials exhibit significant magnetization; nevertheless, this magnetization disappears as the field is withdrawn. This special characteristic makes the nanoparticles particularly valuable in applications such as medication administration, where they may be securely disengaged when their duty is finished and guided and manipulated using external magnetic fields [23-24]. Furthermore, targeted drug delivery systems, hyperthermia treatment, and imaging, such as magnetic resonance imaging or MRI, have adopted these nanoparticles. The materials are extremely excellent for such a non-invasive alternative treatment because of their specific and controllable magnetic characteristics. For example, magnetic nanoparticles can be used in the administration of cancerous treatments to contribute greatly to killing tumor cells via the application of heat without endangering adjacent healthy tissues [25]. The functionality of such magnetic nanoparticles would significantly depend on their stability and the process of manufacturing. Usually, MNPs are coated with silica or polymers to prevent the oxidation of particles, aggregation, and degradation over time while retaining the original magnetic properties [25]. Furthermore, by adjusting their size and composition, the magnetic properties would be fine-tuned for the intended application; hence, one could expect advancements in such areas as environment remediation, energy storage, and biomedicine [26]. Because of these properties, magnetic nanoparticles are one of the major interesting objects and offer brilliant prospects for future technologies in a broad number of industries. This encompasses affecting size and structure but also the content of nanomaterials that can all have significant effects on magnetic properties. Below are some important categories of magnetic properties present in nanomaterials, along with links to known studies-

4.1 Superparamagnetism

The term Superparamagnetism describes a characteristic of very small magnetic nanoparticles, typically on the order of less than 10-20 nm. In the absence of an external magnetic field, thermal energy within this size is enough to randomly flip the direction of magnetization of these particles, resulting in no net magnetization. However, the particles quickly align with a magnetic field, which makes them useful for applications such as drug injection and magnetic resonance imaging (MRI) [27]. Unlike larger ferromagnetic materials, superparamagnetic particles lack permanent magnetic domains. Particle aggregation is prevented when the external magnetic field is withdrawn, which is advantageous for biological applications such as MRI contrast agents and hyperthermia. Superparamagnetism is one of the most important magnetic properties of nanoparticles, especially those smaller than a few nanometers. Under this condition, magnetic nanoparticles are likely to behave magnetically if subjected to an external magnetic field and lose it instantaneously if the latter is removed from their environment, which has particularly proved useful for biological applications such as enhancing the contrast of MRI images and delivering drugs [28-31].

4.2 Ferrimagnetism

Materials such as magnetite (Fe_3O_4) and maghemite (γ-Fe_2O_3) exhibit ferrimagnetism due to the uneven magnitudes of the magnetic moments of ions in separate sublattices oriented in opposing directions, resulting in a net magnetization. This property is what iron oxide nanoparticles so often have and are very important for applications in magnetic data storage and environmental cleanup. Ferrimagnetic material has a net magnetic moment due to their imbalanced magnetic moments which have opposite orientations. Many iron-oxide-based nanoparticles are used to make magnetic storage of information and spintronics materials because of their high magnetism, for example, magnetite (Fe_3O_4) and maghemite (γ-Fe_2O_3). At the nanoscale, ferrimagnetism can still be crucial in nanoparticles. Variables such as particle size and surface spin disorder, for example, affect the performance of the material. For example, since surface effects are larger in smaller particles, ferrimagnetic behavior is often less pronounced [32-34]. Here, $CoFe_2O_4$ nanoparticle research indicates that due to their ferrimagnetic properties, they can be used in magnetic hyperthermia as a cancer therapy. Because of its significant magnetization at ambient temperature, $CoFe_2O_4$ nanoparticles display ferrimagnetism and have been investigated for application in spintronics and magnetic hyperthermia [35-37].

4.3 Superconductivity & magnetism

Certain nanomaterials, particularly those synthesized for particular high-tech applications, sometimes show superconductivity i.e., they extinguish electrical resistance below a certain temperature. These materials can also be found to exhibit diamagnetic properties in some cases that permit them to expel magnetic fields (the Meissner effect), useful for magnetic levitation and high-technology electronics [38]. The nanostructured superconductors, such as yttrium barium copper oxide (YBCO), have been demonstrated to do so because of their distinct magnetic responses at low temperatures. Such superconductors have a high surface-to-volume ratio and can affect electron pairing and flux pinning; hence, their characteristics can be improved if in nanoparticle form.

4.4 Giant Magnetoresistance

Magnetoresistance describes how the electrical resistance of a material changes in response to an applied external magnetic field. Yet another dramatic manifestation of this effect is giant magnetoresistance (GMR), observed at the nanoscale in alternating layers of magnetic and nonmagnetic material. GMR has permitted extremely high data densities on hard drives and thus made PO a storage revolution [39]. Magnetoresistance is the change in electrical resistance of a material that is caused by an external magnetic field. Giant magnetoresistance, or GMR, discovered by nanomaterials, such as stacked Co/Cu nanoparticles, has altered the method of executing data-storage techniques. An external field aligns the magnetic layers of GMR devices such as Co/Cu multilayer nanocylinders, and they offer a huge decrease in their electrical resistance. This effect is of great importance to spintronic devices, besides helping in the development of extremely sensitive magnetic sensors. Co/Cu nanocylinders have demonstrated strong current-in-plane gigantic magnetoresistance in research, which indicates that such materials have interesting applications in data storage technologies [40]. The phenomenon observed in magnetic nanoparticles is named exchange bias, which appears as a shift in the hysteresis loop due to an interaction between ferromagnetic and antiferromagnetic materials. Such a system should exhibit an important characteristic related to magnetic states, specifically for magnetic memory storage and spintronic systems [41]. When an antiferromagnetic shell covers the ferromagnetic core of a nanoparticle, as in the case of Fe/FeO nanoparticles, an exchange bias effect arises. Enhancement of thermal stability and coercivity will be beneficial for these memory-related applications and any other technology where stable magnetic behavior is required. Shift in the hysteresis loop, which further leads to the exchange bias phenomenon, occurs due to the interaction between a ferroelectric and an antiferromagnetic material. This interplay also causes a shift in the hysteresis loop, and the phenomenon is referred to as exchange bias; this effect is highly crucial in applications such as magnetic memory, where the stability of the magnetic state is crucial [42]. It was demonstrated that Fe/FeO core-shell nanoparticles show exchange bias, which is essential for optimizing the stability and performance of spintronic memory devices. In the Fe/FeO nanoparticle case, very significant effects of exchange bias were realized, and such effects may potentially be utilized to produce further complex magnetic memory systems.

4.5 Spintronics and Spin-valve effects

It utilizes the inherent spin and charge in electrons, storing and transmitting information. Electron transport that is spin-polarized forms the basis of spin-valves, the technology innovation that went on to revolutionize memory technology. Spin valves introduce alternating layers of magnetic and non-magnetic materials [43-45]. The resistance in a spin valve is dependent on the alignment of the magnetic layer, and this depends on the spin of the electron. Such effects are necessary for advanced computing devices and non-volatile memory. Electron spin control in magnetic nanostructures spawns spintronic phenomena. Improved memory storage in devices based on these phenomena, called spin valves, employs alternate layers of magnetic and non-magnetic materials. It has been demonstrated that the Co/Cu-based multilayer spin-valve effects are essential for magnetic sensing and memory storage applications.

4.6 Magnetic Anisotropy

Magnetic anisotropy is the dependence of magnetic properties on direction. It is highly significant for nanomaterials because they have more atoms on the surface compared to the bulk. Surface anisotropy affects the alignment of magnetic moments. The size, shape, and coatings at the surface of the particles of magnetic nanoparticles can significantly control the anisotropy of the particles. Applications needing steady magnetization, such as permanent magnets and magnetic recording mediums, benefit from high anisotropy in nanoparticles [46]. Magnetic anisotropy and saturation magnetization may be controlled by annealing temperatures, affecting the particle size and surface disorder of co-ferrite nanoparticles embedded in a SiO_2 matrix [41].

4.7 Magnetic Hyperthermia

Magnetic nanoparticles find an application in the form of magnetic hyperthermia, which is exhibited as they undergo an alternating magnetic field and produce heat. This form of heat is a sophisticated form of treatment when used in the treatment of cancer because it can target and destroy cancer cells without damaging surrounding healthy tissues. Magnetic nanoparticles such as Fe_3O_4 generate heat through Neel and Brownian relaxation when an external AC magnetic field is applied to them. This is the property that, through localized heating, is currently being used to kill malignant cells in the case of hyperthermia [47]. Already, there have been experiments where magnetic nanoparticles coated with biocompatible materials can indeed increase their heating effect sufficiently enough to make them a candidate for the new approach in focused cancer treatments [41]. It is the combination of scale effects, surface phenomena, and quantum effects that makes nanomaterials strikingly magnetic. Such characteristics as exchange bias, magnetoresistance, and Superparamagnetism are considered to be the basis for several advanced applications: spintronics and next-generation data storage, medicinal interventions, etc. Scientists always discover new ways in which altering dimensions, composition, or the structure of nanoparticles can boost magnetic properties for various purposes in industry, technology, and biology [48].

5. Transport Properties

Nanomaterials have received plenty of interest for their unique transport capabilities, critical for advances in electronics, thermoelectric, and nanotechnology. This review summarizes current results on the electrical and thermal transport properties of nanomaterials, with emphasis on graphene, carbon nanotubes, and silicon nanowires by mechanisms controlling these materials, such as electron-phonon interactions and examination of backscattering effect sheds light on the presence of nanoscale properties. The electrical shipping houses of nanomaterials are closely impacted by quantum effects and nanoscale dimensions, resulting in special electron mobility and conductivity characteristics compared to bulk substances. Key studies in this topic provide insights into how materials, which include graphene and carbon nanotubes, display unique electron transport capabilities. Huard et al. (2008) check out electron-hollow asymmetry in graphene, locating that electrical contacts have a prime impact on found delivery homes [49]. The electron-hole imbalance because of the metal-"graphene" interface suggests that touch engineering can be a possible method for customizing graphene's electric characteristics, which is essential for growing graphene-primarily based gadgets in nanoelectronics. Davies et al. (2007) look at carbon nanotube-based total composites, mainly the percolation threshold required for conductivity in those materials [50]. Their studies specialize in how carbon-nanotubes build conductive networks inside composites, with the percolation threshold controlling the beginning of conductivity. The switch from insulating to conductive behavior at this threshold distinguishes nanotube composites, implying that nanomaterial composites offer the potential for applications that need lightweight, high-conductivity materials. McEuen et al. investigated the transport characteristics of single-walled carbon nanotubes (SWCNTs) and discovered that these materials exhibit ballistic transport at nanoscale scales. SWCNTs' quasi-one-dimensional form reduces scattering, allowing for fast electron mobility and low resistance, making them perfect for high-speed electronics [51]. This work emphasizes the ability of SWCNTs in miniaturized circuits in which low electron scattering is preferred**.** Thermal transfer in nanoparticles differs significantly from that in bulk materials. This is because of the consequences of quantum confinement and boundary scattering, which reduce heat conduction and boom thermoelectric performance. Nanomaterials have particular thermal homes that make them appealing for thermoelectric and thermal control applications. Hochbaum et al. (2008) examined silicon nanowires and found that tough surfaces can improve thermoelectric performance by decreasing the thermal conductivity of phonons while retaining electric conductivity; roughness promotes phonon scattering [52]. This reduces the thermal conductivity and improves the thermoelectric overall performance of silicon nanowires. It is critical for the production of nanostructured thermoelectric substances that could efficiently convert waste warmness into power. Colin Baker, et al. (2005) gives a detailed take look at phonon delivery in nanostructures, describing how confinement outcomes affect thermal conductivity in nanoscale materials [53]. As phonons hit boundaries extra regularly at the nanoscale, scattering prices upward thrust, lowering thermal conductivity. This effect is especially beneficial in thermoelectric programs, wherein low thermal conductivity is needed to preserve a temperature gradient and boom energy conversion performance. In silicon wire arrays, the size of the nanostructures has a significant impact on ionic transport efficiency. Smaller, more controlled, and uniform silicon nanowires exhibit improved charge separation and transport due to greater active surface area and shorter diffusion routes. Li et al. (2020) investigated the effects of wire diameter and array uniformity on the photocatalytic performance of silicon wire arrays and discovered that size-optimized silicon nanostructures allow for more efficient electron transfer and higher current densities, which is critical for energy conversion applications [54]. Almora et al. (2020) demonstrated that light intensity influences impedance characteristics and ionic mobility in all-solid-state solar cells, emphasizing the importance of ionic transport in influencing charge production and recombination at varying illumination intensities [55]. This has a look at highlights the opportunity to regulate ionic mobility in photovoltaic systems using mild optimization, which would possibly boost electricity seize efficiency in these gadgets.

6. Surface Properties

Nanomaterials, defined by their size at the nanoscale (1–100 nm), have unique properties not found in bulk materials. These properties are mainly influenced by the surface. Quantum effects and high nanoscale confinement due to surface-to-volume ratio. The surface of nanomaterials plays an important role in determining the reactivity, stability, and efficiency of catalytic applications.

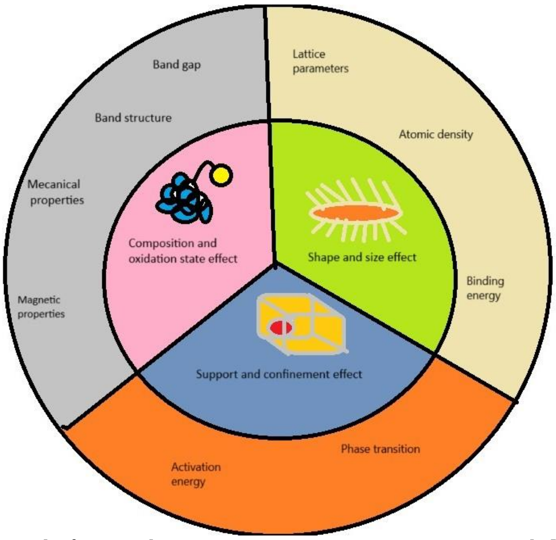


Fig.1:- Multi-functionalization Strategies Using Smart Nanomaterials [56]

When the particle size decreases, a greater proportion of atoms settle on the surface rather than clumping together. For example, the surface of a bulk material can have less than 1% atoms, while a nanoparticle can have 50% or more atoms. This high surface area allows nanomaterials to absorb large amounts of molecules & confirms the high density of surface atoms and is used in gas storage, drug delivery, and sensors [15]. Again, due to a high surface area, gold nanoparticles exhibit admirable catalytic activity compared to bulk gold. Such surface modifications contribute to increased sensitivity, increased conductivity, and multi-functionality. Due to these specific surface properties, nanomaterials are critical in emerging technologies [56]. Research trends similarly focus on optimizing materials and fabrication methods to maximize these surface effects for advanced applications as shown in Fig.1.

7. Applications

Smart nanomaterials are engineered to exhibit particular bodily, chemical, and organic residences because of their nanoscale dimensions. These homes allow them to respond dynamically to environmental stimuli consisting of temperature, light, pH, and magnetic fields. The potential to manipulate these reactions exactly on the nanoscale makes clever nanomaterials exceedingly flexible for diverse applications. They have found massive use in several fields, which include biomedicine, environmental control, textiles, power, and electronics as shown in Fig. 2 [71].

7.1 Biomedical Applications

Quantum dots, iron oxide, gold, and silver nanomaterials are engineered for centered drug transport, imaging, and diagnostics. These substances enhance contrast in imaging strategies, including magnetic resonance imaging (MRI) and computed tomography (CT) scans, supporting a stumble on disorder early [57]. Smart nanomaterials can be engineered to deliver medications directly to cancer cells & reduce harm to healthy tissues and enhance clinical outcomes. For example, nano-carriers such as liposomes, dendrimers, and polymer nanoparticles can deliver treatments directly to cancer cells improving patient outcomes and reducing dosage requirements. Again, smart nanomaterials can also be used in biosensors, which allow to detect the diseases such as foreign biological markers, infections, pollutants, or toxin traces at an early stage. Due to their improved catalytic adsorption properties, nanomaterials such as titanium dioxide (TiO_2) & zinc oxide (ZnO) used in air and water purification systems are effective photocatalysts and can degrade pollutants and organic impurities under ultraviolet light or visible light. This property is particularly useful in the production of self-cleaning surfaces and coatings [24].

7.2 Smart Textiles and Consumer Products

The integration of smart nanomaterials in the textile industry has revolutionized the development of smart clothing and wearable technology. These fabrics combine nanomaterials such as carbon nanotubes, graphene, and nanofibers, giving them properties such as electrical conductivity and heat control. Responding to environmental stimuli, for example, nanomaterial-strengthened fabric can come across modifications in frame temperature or humidity tiers, presenting actual-time remarks on fitness monitoring. Nanomaterials are also being used to increase fabric with antimicrobial properties. UV protection and self-cleaning make the fabric more durable and hygienic. These improvements not only benefit customers in their daily lives. But there are also more specialized areas such as healthcare, navy, and sports activities [58-60].

7.3 Energy Harvesting and Storage

Smart nanomaterials have shown great potential in energy harvesting and storage technology. Nanomaterials such as perovskites and quantum dots have been used to increase the efficiency of solar cells in applications. This allows for better absorption of sunlight and electrical conversion. Adjustable electrical properties and low-temperature processing capability make them a cost-effective alternative to conventional silicon solar cells [61-63]. Nanomaterials for energy storage contribute to the development of advanced batteries and supercapacitors with higher energy densities, which help in faster charging time and longer lifespan. For example, graphene and carbon nanotubes are used in electrode materials to improve the electrical conductivity and stability of lithium-ion batteries. These advances are important in the transition to electric vehicles and renewable energy systems [24].

7.4 Smart Nanomaterials in Electronics

The electronics zone benefits substantially from the particular use of smart nanomaterials. Nanomaterials are used in design and adaptable electrical gadgets which include graphene and carbon nanotubes. Silver nanowires can be used to create displays, sensors, and wearable electronics [64 & 65]. Smart nanomaterials are also important in improving data storage, memory, and computation. Incorporating nanoparticles into memory devices increases data storage capacity and processing velocity. Smart nanomaterials can stimulate the artificial neural community of the human brain for mapping and different health treatments. Neuromorphic processing makes use of nanomaterial-based totally additives to mimic the synapse feature, which paves the way for greater green and adaptable synthetic intelligence systems [24].

7.5 Self-healing smart nanomaterials:

Smart nanomaterials contribute to the development of self-healing composite coating polymers that can self-repair damaged materials using microcapsule-like nanomaterials filled with healing materials or shape-memory alloys at the expense of these materials for a specific stimulus, such as heat or pressure. Get in touch and restore your structure. The technology is valuable in the construction, automotive, and aerospace industries, where it needs to be durable [66 & 67].

7.6 Catalysis and automotive industry

Nanomaterials, with their excessive floor area and specific reactivity, are used as catalysts to boost chemical reactions. It is primarily effective in enterprise methods such as petroleum refining. Production of chemical compounds and reducing greenhouse gas emissions Smart catalytic nanomaterials, such as platinum or palladium nanoparticles, help increase the efficiency of the reaction [24]. Reduce energy use and reduce waste, thus helping to promote more sustainable commercial practices. The aerospace and automobile industries use smart nanomaterials to grow lightweight yet strong materials to improve the performance and efficiency of gasoline. Carbon nanotubes and graphene are used in a composite to decorate a mechanical housing without significantly increasing its weight. These top-notch composite materials are used in aircraft, satellites, and high-performance motors, which is necessary to lose weight [68].

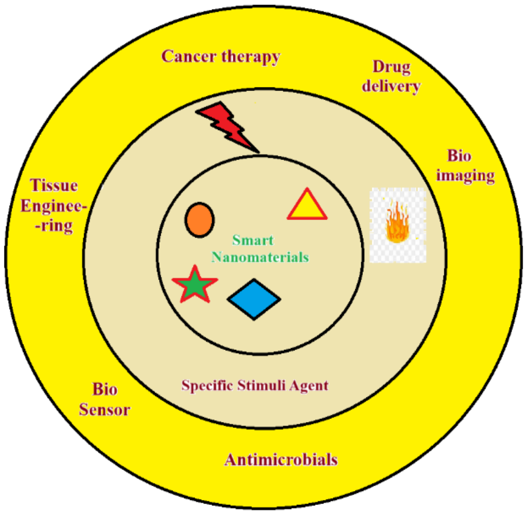


Fig.2 - Application & uses of smart nanomaterials [69]

8. Results & Discussion

The thorough review of magnetic, transport, and surface properties of smart nanomaterials reveals important progress and trends currently transforming, and continue to transform technologies and practices. In terms of magnetic properties, much work has been done on superparamagnetic nanoparticles, particularly with iron oxide-based nanoparticles, including Fe_3O_4 and γ-Fe_2O_3, which have been useful for important biomedical work (e.g. magnetic resonance imaging (MRI), magnetic hyperthermia therapy, targeted and local drug delivery) [23-24]. There has also been a great deal of research on ferrimagnetism [27-31], exchange bias [40], and spintronic phenomena [43-45] in these nanomaterials that could further lead to advances in high-density magnetic storage and devices based on spin-degrees of freedom. The synthesis (size, morphology, and surface coatings) and characterizations of magnetic nanoparticles have been important in stabilizing the magnetic stability, biological functionality, and biocompatibility of these nanoparticles. Smart nanomaterials, such as carbon nanotubes, graphene, and silicon nanowires, show unique electron and phonon transport properties [49, 51-52] and these properties mainly stem from quantum confinement effects and reduced scattering due to output scale correlative phenomena. For example, single-walled carbon nanotubes showed the ballistic transport behavior of electrons, which can be advantageous for manufacturing high-speed, low-power nanoelectronics. With thermoelectric, it has been shown that by engineering the surface roughness of silicon nanowires, thermal conductivity can be reduced without affecting electrical conductivity. This will result in increased thermoelectric efficiency due to lowered thermal conductivity. These unique transport behaviors create opportunities for nanomaterials to be used in energy-harvesting devices, flexible electronics, and next-generation sensors. Surface properties significantly affect the functionality and application of nanomaterials. Regardless, nanomaterials do exhibit higher chemical reactivity, catalytic activity, and adsorption ability due to the large surface-area-to-volume ratio [15 & 56]. Surface functionalization, such as the attachment of ligands, encapsulation of polymers, or surface doping, has provided the ability to organize multifunctional nanomaterials that provide simultaneous sensing, imaging, drug delivery, and environmental remediation [56]. Surface engineering and chemistry are important strategies in enhancing selectivity, sensitivity, and stability in technology-applied disciplines. The cross-examination of the latest studies found that there has been considerable advancement toward independently optimizing magnetic, transport, and surface properties; however, merging these features into one multifunctional nanostructure remains a challenging pursuit. Continuous integration of functionality would propel transformational advances in personalized medicine, nanoelectronics, smart energy systems, and adaptive materials [71]. Despite advances being made, several major issues remain. The large-scale, cost-effective synthesis of smart nanomaterials (across all three descriptors), while sustaining reproducibility remains difficult. Additionally, environmental impact, biocompatibility, and long-term operational stability need systematic attention. In the future co-innovation should focus on integrating green synthesis, the development of biodegradable nanomaterials, and hybrid organic-inorganic systems that maximize performance and environmental sustainability. In summary, the interdisciplinary development of smart nanomaterials emphasizes the transformative potential of simply employing novel nanomaterials that have magnetic, transport, and surface properties. Future innovation, combined with scalable fabrication and environmental safety, will be key to realizing the potential of smart nanostructures that enable future scientific and technological advances.

9. Challenges and Future Directions

Despite the promising applications of smart nanomaterials, many challenges remain. Issues related to scalability, cost, and potential environmental and health impacts. Need to be fixed. Research is ongoing on developing green synthesis methods and biodegradable nanomaterials to reduce environmental risks. Standardizing safety guidelines and procedures for the handling and disposal of nanomaterials is critical to reducing potential hazards [70]. The destiny of smart nanomaterials depends on the convergence of disciplines which include substances technological know-how, chemistry, biology, and engineering. As our expertise in nanoscale interactions improves, it's far anticipated that greater complicated & numerous nanomaterials could be developed and can cause upgrade energy performance and advanced computer generation [71].

10. Conclusions

The study of magnetic, transport, and surface properties of smart nanomaterials is of paramount importance due to their wide-ranging applications in cutting-edge technologies. Magnetic properties enable advancements in data storage, magnetic sensing, and biomedical applications such as targeted drug delivery and imaging. The transport properties, including electrical and thermal conductivity, are critical for the development of efficient energy storage systems, electronic devices, and nanoscale sensors. Additionally, the surface properties of smart nanomaterials play a pivotal role in enhancing their functional performance in catalysis, environmental remediation, and biomedical interfaces. By comprehensively understanding and controlling these properties, researchers can design tailored materials with enhanced performance, addressing both scientific and industrial challenges. This review highlights the interdisciplinary nature of smart nanomaterials and underscores their potential to drive innovation in fields ranging from healthcare to sustainable energy, paving the way for next-generation technologies. In the future, we anticipate that smart nanomaterials will achieve multifunctionality by uniting magnetic, electronic, and surface-sensitive actions in one system. Research attention should be given to the scalable and low-cost synthesis of smart nanomaterials with controlled size, composition, and surface chemistry. It will also be important to set guidelines for facilities to use eco-friendly, biodegradable nanomaterials to minimize environmental impacts. New areas of innovation include nanorobotics, personalized nanomedicine, quantum computing, and flexible electronics, where smart nanomaterials will have a critical impact. We also expect the growth of interdisciplinary practices across material science, biotechnology, and Artificial Intelligence to contribute to our ability to discover, apply, and implement new generations of smart materials, leading to more sustainable, efficient, and intelligent technologies.

Data Availability
No primary data were generated or analyzed for this study. Data sharing is not applicable. However, any supporting material can be made available upon reasonable request.

Conflict of Interest
The authors declare that there is no conflict of interest.

Funding Source
This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Authors' Contributions
Om Prakash & Ananya: Writing – Original Draft & Figure Creation. S.K. Parida: Writing – Reviewing & Editing, Visualization & Supervision.

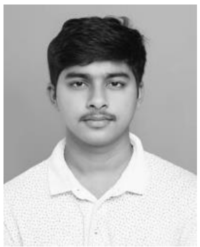
Acknowledgments
The authors would like to thank to host Institute for providing the digital library facility during the period of literature survey and finalization of the manuscript.

References

[1] B. Viswanathan, Nanomaterials. Narosa Publishing House, pp. 1–250, 2014.
[2] J.Z. Zhang, Optical Properties and Spectroscopy of Nanomaterials. World Scientific, 2009.
[3] P.R. Sajanlal, T.S. Sreeprasad, A.K. Samal, and T. Pradeep, "Anisotropic nanomaterials: structure, growth, assembly, and functions," Nano Reviews, vol. 2, no. 1, p. 5883, 2011.
[4] J.T. Lue, "Physical properties of nanomaterials," Encyclopedia of Nanoscience and Nanotechnology, vol. 10, no. 1, pp. 1–46, 2007.
[5] D. Vollrath and W.V.V.G.C. KGaA, "An introduction to synthesis, properties and application," Management, vol. 7, no. 6, pp. 865–870, 2008.
[6] F.J. Heiligtag and M. Niederberger, "The fascinating world of nanoparticle research," Materials Today, vol. 16, no. 7–8, pp. 262–271, 2013.
[7] P. Walter, et al., "Early use of PbS nanotechnology for an ancient hair dyeing formula," Nano Letters, vol. 6, no. 10, pp. 2215–2219, 2006.
[8] J. Jeevanandam, et al., "Review on nanoparticles and nanostructured materials: history, sources, toxicity and regulations," Beilstein Journal of Nanotechnology, vol. 9, no. 1, pp. 1050–1074, 2018.
[9] I. Freestone, et al., "The Lycurgus cup—a Roman nanotechnology," Gold Bulletin, vol. 40, pp. 270–277, 2007.
[10]William William D. Callister and D.G. Rethwisch, Materials Science and Engineering: An Introduction. John Wiley & Sons, ch. 1, pp. 4, 7, 2020.
[11]Michel Barsoum, Fundamentals of Ceramics. CRC Press, ch. 1, pp. 4–5, 2019.
[12]Xuewei Zhang, Tianbiao Yu, & Ji Zhao, "An analytical approach on a stochastic model for cutting force prediction in milling ceramic matrix composites," International Journal of Mechanical Sciences, vol. 168, p. 105314, 2020.
[13]Ibrahim Khan, Khalid Saeed, Idrees Khan, "Nanoparticles: Properties, applications and toxicities," Arabian Journal of Chemistry, vol. 12, no. 7, pp. 908–931, ISSN 1878-5352, 2019.
[14]Wenwen Liu, et al., " Graphene quantum dots-based advanced electrode materials: design, synthesis and their applications in electrochemical energy storage and electrocatalysis," Advanced Energy Materials, vol. 10, no. 29, p. 2001275, 2020.
[15]Nadeem Baig, Irshad Kammakakam, and Wail Falath, "Nanomaterials: A review of synthesis methods, properties, recent progress, and challenges," Materials Advances, vol. 2, no. 6, pp. 1821–1871, 2021.
[16]Nadeem Joudeh, and Dirk Linke, "Nanoparticle classification, physicochemical properties, characterization, and applications: a comprehensive review for biologists," Journal of Nanobiotechnology, vol. 20, no. 1, p. 262, 2022.
[17]Paul Alivisatos, "The use of nanocrystals in biological detection," Nature Biotechnology, vol. 22, no. 1, pp. 47–52, 2004.
[18]Erik Garnett, Liqiang Mai, and Peidong Yang, "Introduction: 1D nanomaterials/nanowires," Chemical Reviews, vol. 119, no. 15, pp. 8955–8957, 2019.
[19]A.K. Geim and K.S. Novoselov, "The rise of graphene," Nature Materials, vol. 6, no. 3, pp. 183–191, 2007.
[20]Guangqing Ming, Siling Chen, B ingxun Li, Fengfeng Li, Liwu Liu, Yanju Liu & Jinsong Leng, " Design, fabrication and experimental verification of a drag sail based on thermal-driven controllable bi-stable shape memory polymer composite booms," Smart Materials and Structures, vol. 33, no. 5, p. 055040, 2024.
[21]X. Li, et al., " Dimensional diversity (0D, 1D, 2D, 3D) in Perovskite solar cells: Exploring the potential of mix-dimensional integrations," Journal of Materials Chemistry A, 2024.
[22]Miko Yamada, and Tarl W. Prow., " Physical drug delivery enhancement for aged skin, UV damaged skin and skin cancer: Translation and commercialization," Advanced Drug Delivery Reviews, vol. 153, pp. 2–17, 2020.
[23]Saima Gul, et al., "A comprehensive review of magnetic nanomaterials modern day theranostics," Frontiers in Materials, vol. 6, p. 179, 2019.
[24]Magdalena Aflori, "Smart nanomaterials for biomedical applications—A Review," Nanomaterials, vol. 11, p. 396, 2021.
[25]K.K. Patankar and C.M. Hussain (Eds.), Fundamentals and Industrial Applications of Magnetic Nanoparticles. Woodhead Publishing, 2022.
[26]Suresh Thangudu, "Next generation nanomaterials," Applications of Nanomaterials in Human Health, pp. 287–312, 2020.
[27] M. Mabrouk, D.B. Das, Z.A. Salem & H.H. BehereiCombination of Discrete Transformation and Matrix Reduction," *International Journal of Scientific Research Biological Sciences*, Vol.5, No.1, pp.1-6, 2017.
[28]Shubham Rajput, S.D. Tiwari, "Interparticle interaction effect on superparamagnetic properties of ferrimagnetic particles," Journal of Magnetism and Magnetic Materials, vol. 611, p. 172603, 2024.
[29]T.D. Clemons, R.H. Kerr, and A. Joos, " MultifunctionalMagnetic Nanoparticles: Design, Synthesis, andBiomedical Applications," Comprehensive Nanoscience and Nanotechnology, pp. 193–210, 2018.
[30]M. Montazer and T. Harifi, "Magnetic nanofinishes for textiles," Nanofinishing of Textile Materials, pp. 225–240, 2017.
[31]NM Hosny, A Hazem, SM Moalla, "Synthesis, characterization and analytical applications of cobalt ferrite nanoparticles," Chemical Data Collections, vol. 42, p. 100948, 2022.
[32]Yichen Liu, San-Dong Guo, Yongpan Li, and Cheng-Cheng Liu, "Two-dimensional fully compensated ferrimagnetism," *Phys. Rev. Lett.*, vol. 134, p. 116703, 2025.
[33] V. Baltz, A. Manchon, M. Tsoi, T. Moriyama, T. Ono, and Y. Tserkovnyak, "Antiferromagnetic spintronics," Rev. Mod. Phys., vol. 90, p. 015005, 2018.
[34]L. Smejkal, J. Sinova, and T. Jungwirth, "Emerging landscape of altermagnetism," Phys. Rev. X, vol. 12, p. 040501, 2022.
[35]I. Mazin, "Editorial: Altermagnetism —a new punch line of fundamental magnetism," Phys. Rev. X, vol. 12, p. 040002, 2022.
[36]H. van Leuken and R. A. de Groot, "Half-metallic antiferromagnets," Phys. Rev. Lett., vol. 74, p. 1171, 1995.
[37]H. Akai and M. Ogura, "Half-metallic diluted antiferro magnetic semiconductors," Phys. Rev. Lett., vol. 97, p. 026401, 2006.
[38]J. Bardeen, L.N. Cooper, and J.R. Schrieffer, "Microscopic theory of superconductivity," Phys. Rev., vol. 106, p. 162, 1957.
[39]Debakanta Samal & P. S. Anil Kumar, E.Y. Tsymbal and D. Pettifor, "Perspectives of giant magnetoresistance," Solid State Physics, vol. 56, pp. 113–237, 2001.
[40]E.Y. Tsymbal and D.G. Pettifor, "Perspectives of giant magnetoresistance," Solid State Physics, vol. 56, pp. 113–237, 2001.
[41]P. Arosio, "Applications and properties of magnetic nanoparticles," Nanomaterials, vol. 11, no. 5, p. 1297, 2021.
[42]K.Y. Kok and I.K. Ng, "Giant Magnetoresistance (GMR): spinning from research to advanced technology," ASEAN Journal on Science and Technology for Development, vol. 19, pp. 33–43, 2002.

[43]A. Hirohata, K. Yamada, Y. Nakatani, I. L. Prejbeanu, B. Diény, P. Pirro & B. Hillebrands," Review on spintronics: Principles and device applications," Journal of Magnetism and Magnetic Materials, vol. 509, p. 166711, 2020.
[44]I.A. Iusipova and A.I. Popov, "Spin valves in microelectronics," Semiconductors, pp. 1–13, 2021.
[45]B. Dieny, R.C. Sousa, J. Herault, C. Papusoi, G. Prenat, U. Ebels, & I .L. Prejbeanu, " Spin-transfer effect and its use in spintronic components," International Journal of Nanotechnology, vol. 7, no. 4–8, pp. 591–614, 2010.
[46]J.C. Slonczewski, "Magnetic anisotropy in magnetite," Physical Review, vol. 110, no. 6, p. 1341, 1958.
[47]H. Fatima, T. Charinpanitkul, and K.S. Kim, " Fundamentals to apply magnetic nanoparticles for hyperthermia therapy," Nanomaterials, vol. 11, no. 5, p. 1203, 2021.
[48]Suresh Thangudu, " Next generation nanomaterials: smart nanomaterials, significance, and biomedical applications," Applications of Nanomaterials in Human Health, pp. 287–312, 2020.
[49]B. Huard, et al., " Evidence of the role of contacts on the observed electron-hole asymmetry in graphene," Phys. Rev. B, vol. 78, no. 12, p. 121402, 2008.
[50]P. Davies, C. Morvan, O. Sire, & C. Baley., " Structure and properties of fibers from seagrass (Zostera marina)," Journal of Materials Science, vol. 42, pp. 4850–4857, 2007.
[51]P.L. McEuen, M.S. Fuhrer, and H. Park, "Single-walled carbon nanotube electronics," IEEE Transactions on Nanotechnology, vol. 1, no. 1, pp. 78–85, 2002.
[52]A.I. Hochbaum, R. Chen, R.D. Delgado, W. Liang, E.C. Garnett, M. Najarian, A. Majumdar, and P. Yang, "Enhanced thermoelectric performance of rough silicon nanowires," Nature, vol. 451, no. 7175, pp. 163–167, 2008.
[53]C. Baker, A. Pradhan, L. Pakstis, D.J. Pochan, and S.I. Shah, "Synthesis and antibacterial properties of silver nanoparticles," Journal of Nanoscience and Nanotechnology, vol. 5, no. 2, pp. 244–249, 2005.
[54]L. Liujing, Y. Xiong, W. Zhang, Z. Wang, X. Wen, and X. Li, "Size-dependent performances inhomogeneous, controllable, and large-area silicon wire array photocathode," Journal of Power Sources, vol. 473, p. 228580, 2020.
[55]Almora Osbel, C. Aranda, G. Garcia-Belmonte, J. Bisquert, and H. Garcia, "Light intensity modulated impedance spectroscopy (LIMIS) in all-solid-state solar cells at open-circuit," Journal of Power Sources, 2020.
[56]J.H. Song, S.H. Min, S.G. Kim, Y. Cho, and S.H. Ahn, "Multi-functionalization strategies using nanomaterials: A review and case study in sensing applications," International Journal of Precision Engineering and Manufacturing-Green Technology, vol. 9, no. 1, pp. 323–347, 2022.
[57]S. Thangudu, "Next generation nanomaterials: smart nanomaterials, significance, and biomedical applications," Applications of Nanomaterials in Human Health, pp. 287–312, 2020.
[58]M.A. Shah, B.M. Pirzada, G. Price, A.L. Shibiru, and A. Qurashi, "Applications of nanotechnology in smart textile industry: A critical review," Journal of Advanced Research, vol. 38, pp. 55–75, 2022.
[59]Nazire Deniz Yilmaz,(Ed.), Smart Textiles: Wearable Nanotechnology. John Wiley & Sons, 2018.
[60]T.I. Shaheen, " Nanotechnology for modern textiles: highlights on smart applications," The Journal of The Textile Institute, vol. 113, no. 10, pp. 2274–2284, 2022.
[61]R. Sabo, A. Yermakov, C.T. Law, and R. Elhajjar, "Nanocellulose-enabled electronics, energy harvesting devices, smart materials, and sensors: A review," Journal of Renewable Materials, vol. 4, no. 5, pp. 297–312, 2016.
[62]A. Nayak, V.K. Saini, and B. Bhushan, "Nanomaterials for energy harvesting and storage: an overview," Applications of Nanomaterials in Agriculture, Food Science, and Medicine, pp. 188–203, 2021.
[63]Anupma Thakur, Pooja Devi, "Based flexible devices for energy harvesting, conversion, and storage applications: A review," Nano Energy, vol. 94, p. 106927, 2022.
[64]Azamal Husen, Khwaja Salahuddin Siddiqi (Eds.), Advances in Smart Nanomaterials and Their Applications. Elsevier, 2023.
[65]Hoang-Phuong Phan, "Implanted flexible electronics: Set device lifetime with smart nanomaterials," Micromachines, vol. 12, no. 2, p. 157, 2021.
[66]Dashuai Yan, Zhenhua Zhang, Wenjia Zhang, Yanli Wang, Meng Zhang, Tao Zhang, Jun Wang, "Smart self-healing coating based on the highly dispersed silica/carbon nanotube nanomaterial for corrosion protection of steel," Progress in Organic Coatings, vol. 164, p. 106694, 2022.
[67]Tao Qin, Xukai Li , Anqi Yang , Meng Wu , Li Yu , Hongbo Zeng , Linbo Han, "Nanomaterials-enhanced, stretchable, self-healing, temperature-tolerant and adhesive tough organohydrogels with long-term durability as flexible sensors for intelligent motion-speech recognition," Chemical Engineering Journal, vol. 461, p. 141905, 2023.
[68]Harun-Ur-Rashid, M., & A. B. Imran, "Nanomaterials in the automobile sector," in Emerging Applications of Nanomaterials, Materials Research Forum LLC, vol. 141, pp. 124–150, 2023.
[69]Firdos Alam Khan, and F. Khan, Applications of Nanomaterials in Human Health. Springer, Singapore, 2020.
[70]Akintunde O. Onamade, Opeyemi A. Asaju, Bamidele J. Adewumi, "Challenges and prospects of smart nanomaterials for environmental remediation," Smart Nanomaterials for Environmental Applications, pp. 757–780, 2025.
[71]Arnav Tripathy, Akshata Y. Patne, Subhra Mohapatra and Shyam S. Mohapatra, "Convergence of nanotechnology and machine learning: The state of the art, challenges, and perspectives," International Journal of Molecular Sciences, vol. 25, no. 22, p. 12368, 2024.

AUTHORS PROFILE



Om Prakash Hota completed his graduation in Physics (Hons) at Gayatri +3 Science College (2020-2023) at Utkal University, Bhubaneswar. Currently, he is pursuing his Master's degree in Physics at Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar for the 2023–2025 session.

Ananya Jena completed her graduation in physics (Hons) at sulagna +3 science Degree College, Balasore under Fakir Mohan University, Balasore. Current she is pursuing her Master's degree in physics at Siksha 'O' Anusandhan (Deemed to be university) Bhubaneswar for the 2023-2025 session.

Dr. Santosh Kumar Parida is working as an Associate Professor in Physics in the ITER, Siksha O Anusandhan Deemed to be University, Bhubaneswar, Odisha, India. He received his Master's degree and MPhil in Physics (in 2002 & 2003) from Sambalpur University, Sambalpur, Odisha, India. Then, he received his Ph.D. degree in Condensed Matter Physics (Experimental) from the Department of Physics, Siksha O Anusandhan Deemed to be University, Odisha, India in the year 2015. He has more than 23 years of teaching experience. He has published 105 International peer-reviewed SCI journals (Wiley. Elsevier, Springer, America Scientific Publisher, Bentham Science & Taylor and Francis, etc.) and 6 conference proceedings. He has contributed 6 book chapters in edited books (Scopus) and presented his research papers in more than 20 National and International Conferences. He was nominated as Top 2% of World Scientists, in 2023 & 2024 (Stanford University, USA). He is a guest editor of International peer-reviewed journals & also works as a reviewer for more than 40 Scopus and SCI-indexed journals.