Chapter 3
Advancements in Designing Smart and Intelligent Nanocoatings

Mukhtar Iderawumi Abdulraheem
https://orcid.org/0000-0002-6745-378X
Henan Agricultural University, China

Abiodun Yusuff Moshood
https://orcid.org/0000-0002-0917-8396
Henan Agricultural University, China

Yongqi Chen
Henan Agricultural University, China

Hongjun Chen
Henan Agricultural University, China

Haiyan Zhang
Henan Agricultural University, China

Jiandong Hu
Henan Agricultural University, China

ABSTRACT

Smart and intelligent nanocoatings have emerged as crucial components in various industries, offering enhanced functionalities and improved performance. This chapter explores the recent advancements in studying smart and intelligent nanocoatings, encompassing their design, synthesis, characterization, and applications. The chapter aims to provide a comprehensive understanding of the current state-of-the-art in this field and highlight the potential for future development and research. This chapter concluded that developing smart and intelligent nanocoatings has significantly enhanced various industries' performance, durability, and safety. However, future research focuses on reducing costs, scaling up production, and creating more advanced systems with existing technologies, such as sensors and actuators.

DOI: 10.4018/979-8-3693-3136-1.ch003

INTRODUCTION

Advanced nanocoatings that utilize nanotechnology and possess responsive or adaptive properties are known as competent and intelligent coatings (Abdel-Karim and Waheed, 2013; Girigoswami et al., 2022; Nile et al., 2020). These coatings are highly versatile and designed to sense and respond to changes in their surroundings, making them capable of performing various functions (Cao et al., 2022; Cerqueira et al., 2017; Malik et al., 2023). Intelligent nanocoatings have garnered significant attention in recent years, with potential applications across various industries (Cerqueira et al., 2017). To fully grasp the importance of studying smart nanocoatings, it is necessary to define key terms and concepts. Nanocoatings are thin films or layers, typically measured in nanometers (one billionth of a meter), and applied to surfaces to enhance their properties, such as durability, corrosion resistance, self-cleaning ability, or antimicrobial activity (Vasile, 2018). Nanotechnology involves manipulating materials at the nanoscale (typically between 1 and 100 nanometers) to achieve unique properties and functionalities. Advanced nanocoatings go beyond regular coatings by incorporating responsive elements into their composition. External factors such as temperature, light, humidity, pH, or mechanical stress can trigger these responsive elements. By responding to these factors, smart nanocoatings can change their properties in a controlled manner. The study of intelligent nanocoatings is vital for numerous reasons, including:

1. These coatings can revolutionize various industries by offering improved functionality and performance.
2. They provide solutions to challenges traditional coatings face, such as limited durability or a lack of adaptability.
3. Smart nanocoatings can contribute to sustainability efforts by reducing the need for frequent reapplications or maintenance. Intelligent nanocoatings have a wide range of applications across various industries. In the automotive industry, they can create self-healing surfaces that automatically repair minor scratches or damages, improving the aesthetics and extending the lifespan of vehicles (Thakur and Kumar, 2022).
4. These coatings can provide anti-fogging properties for windshields or windows, enhancing visibility and safety.

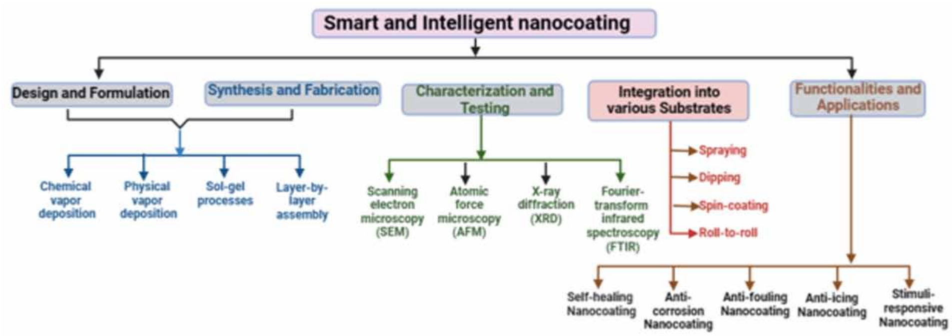
In food packaging, intelligent and innovative nanocoatings are quickly gaining popularity for their ability to enhance packaged food items' safety, quality, and longevity (Ashfaq et al., 2022; Singh et al., 2023). These coatings offer a range of functionalities, such as antimicrobial properties, gas barrier properties, and sensing capabilities. With advancements in developing these intelligent nanocoatings, the food packaging industry has revolutionized, providing improved protection against contamination, spoilage, and degradation (Girigoswami et al., 2022; Motelica et al., 2020). One of the most significant advancements in designing intelligent nanocoatings for food packaging is the integration of antimicrobial agents. These agents help to impede the growth of harmful bacteria, fungi, and other microorganisms on the surface of packaging materials, thereby minimizing the risk of foodborne illnesses (Jagtiani, 2022). Silver nanoparticles (AgNPs) are commonly used as antimicrobial agents due to their exceptional antibacterial properties (Singh et al., 2023). They can be integrated into the nanocoating formulation or applied as a separate layer on the packaging material. When silver ions are released from the nanoparticles, they disrupt the cellular processes of microorganisms, leading to their inactivation (Sharma et al., 2017).

Furthermore, intelligent nanocoatings can create flexible and stretchable electronics by providing a protective layer that can withstand mechanical stress. Smart nanocoatings also have significant potential in the healthcare sector (Ortega-Nieto et al., 2023). They can be used to develop antimicrobial coatings for medical devices or surfaces in healthcare facilities, thereby reducing the risk of infections (Blum et al., 2015; Sadabadi et al., 2022). Smart nanocoatings have potential applications in various industries, from energy-efficient buildings with self-regulating temperature control to anti-graffiti coatings (Fig. 1) that repel paint or ink and self-cleaning coatings for solar panels to maintain optimal efficiency (Idumah et al., 2020; Young et al., 2020). The advantages of these coatings are numerous, including enhancing the durability and lifespan of surfaces, reducing maintenance costs, improving energy efficiency, providing antimicrobial properties, enabling targeted drug delivery systems (Pham et al., 2020), and contributing to sustainability efforts.

Developing nanocoatings with gas barrier properties is a significant breakthrough in food preservation, where oxygen and moisture are two culprits that contribute to food spoilage and degradation (Girigoswami et al., 2022; Ros-Lis and Benitez Serra, 2023). Nanocoatings can be engineered to create a barrier against these gases, effectively preventing them from permeating packaged the food (Ashfaq et al., 2022). This results in preserving the freshness and quality of the food for an extended period. Nanocomposites, consisting of polymers and nanoparticles like clay or graphene oxide, have shown promising results in enhancing gas barrier properties (Singh et al., 2023; Xie et al., 2019).

Furthermore, intelligent nanocoatings have been developed to provide real-time monitoring and sensing capabilities in food packaging (Jagtiani, 2022). These coatings can detect changes in temperature, pH levels, or gas composition inside the package and provide feedback on the quality and safety of the food product (Motelica et al., 2020). For example, pH-sensitive nanocoatings change color when exposed to acidic or alkaline conditions, indicating potential spoilage or contamination (Ros-Lis and

Figure 1. Processes in smart and intelligent nanocoatings



Benitez Serra, 2023; Sharma et al., 2017). Similarly, temperature-sensitive coatings can alert us if the food has been exposed to improper storage (Sharma et al., 2017). The smart and intelligent nanocoatings field holds immense promise for various industries. These advanced materials can actively sense and adapt to environmental changes by incorporating responsive elements into nanocoatings, benefiting the automotive and aerospace industries, electronics, healthcare sectors, and more (Han et al., 2023; Plazas-Tuttle et al., 2015). The benefits of these coatings include improved durability, enhanced functionality, reduced maintenance costs, increased safety, and sustainability contributions (Abdel-Karim and Waheed, 2013).

DESIGN AND SYNTHESIS OF NANOCOATINGS

Smart nanocoatings are a special kind of advanced material with unique features and abilities at the nanoscale. They are meant to enhance the performance and durability of different surfaces like metals, ceramics, polymers, and glass (Tang et al., 2023; Ulaeto et al., 2019). To create these coatings, precise control over the deposition process is needed to achieve the desired traits, such as better corrosion resistance, self-cleaning properties, anti-fouling behavior, or improved optical properties. Many techniques have been developed to synthesize these smart nanocoatings, including chemical vapor deposition (CVD), sol-gel methods, electrochemical deposition, and self-assembly processes (Figure 1). Table 1 summarizes the coating methods along with their process parameters.

Each of the synthesis technics are further discuss below:

1. **Chemical Vapor Deposition (CVD):** Chemical vapor deposition is commonly used to create accurate thin films and coatings, which involve introducing

Table 1. Comparison and summary of various nanocoatings technologies

Nanocoating Methods	Coating Materials	Process Parameters	Principles	Advantages	Disadvantages	References
CVD	Ceramic, Metallic	Size of nanoparticles, temperature, surface treatments, target materials, deposition time	Production of chemical reaction on solid substances Transferring of the volatile substance to the deposition area	Flexibility, Effectiveness, Purity of material, Processing cost and highly efficiency	Dangerous gas accrual, laborious and require experts	(Abbasi et al., 2020)
Sol-Gel	Nanocomposite, inorganic salt, Metallic	pH, Catalyst nature, initial material to produce sol, Temperature, Hydrolysis ratio	Heat treatment and hydrolysis reaction	Simple, Efficiency, reactions at low temperature, homologous coating with high purity.	Time consuming, high cost of raw materials	(Li et al., 2020; Mohammed and Hussein, 2019; Sun et al., 2019)
Electrochemical deposition	Metallic Matrix, Nanocomposite, Metallic	Current density, Bath temperature and composition, pH, Additive	Deposited on the substrate, materials reach melting state and atomized with airflow	Efficiency deposition, simple, flexibility, wide coating and substrate selection, varying coating thickness	Oxide inclusions due to high temperature, abrasion and hardness resistance of the coating	(Berger, 2015; Li et al., 2017)
Self-Assembly Process	Ceramic, Metallic	Laser power density, cooling density,	Deposition and melting, material are continuously fed	Simple, very fast, low coating dilution rate, effectiveness and efficient, unlimited powder selection	Poor repeatability, coating performance are affected due to porosity and cracks, poor cladding layers	(Li et al., 2017; More et al., 2017)

precursor gas and substrate material into a reaction chamber (Gu et al., 2020; Noah, 2020). The precursor gas undergoes chemical reactions on the substrate surface, producing a solid film. CVD can be performed under different conditions, such as low pressure (LPCVD) or atmospheric pressure (APCVD). Choosing the appropriate precursor gas and reaction conditions enables the synthesis of various smart nanocoatings with custom properties (He et al., 2020). For example, hydrophobic coatings can be created using CVD using precursor gases containing fluorine or silicon atoms (Ramasubramanian et al., 2019). These thin films exhibit water-repellent properties and can be helpful in self-cleaning surfaces or anti-fouling coatings. Although the application of CVD coatings to food processing equipment is limited due to the complex apparatus required and the size and throughput restrictions of the coatings, they offer exceptional results in certain areas (Bastarrachea et al., 2015a). These coatings are beneficial when coating small, irregularly shaped parts that endure significant wear and tear, such as sanitary valve components. The purity and strength of CVD coatings make them a valuable resource for specific applications (Noah, 2020).

2. **Sol-Gel Methods:** The sol-gel process synthesizes metal alkoxides or metal salts in a liquid solution, creating nanocoatings. This process entails producing a sol, a nanoparticle liquid (Vasile, 2018). The sol undergoes aging and drying to form a gel, which can be further processed to create a solid nanocoating (Mohammed and Hussein, 2019). The sol-gel approach provides a variety of advantages when producing smart nanocoatings, including the ability to include functional additives in the coating matrix, such as nanoparticles, organic molecules, or dyes (Farooq et al., 2022). This allows coatings to exhibit specific characteristics, such as increased mechanical strength, optical transparency, or customized surface chemistry. (Moncada et al., 2007; Prasad et al., 2018) has documented the production of hybrid layered aluminosilicate nanoparticles that incorporated octadecyl amine (ODA) as the organic component, along with SiO_2 nanoparticles that had a spherical shape and contained ODA or lacked it (Plazas-Tuttle et al., 2015). These nanoparticles were created using the sol-gel approach and were utilized to create nanocomposites with polypropylene. An instance of smart nanocoating generated through sol-gel methods is photocatalytic coatings that can decompose organic pollutants under UV light exposure (Abdulraheem et al., 2023; Bao et al., 2019). These coatings have numerous applications, including air purification systems and self-cleaning surfaces.
3. **Electrochemical Deposition**: This involves the reduction of metal ions from an electrolyte solution onto a conductive substrate, in which an electric current passing between the substrate and a counter electrode can be achieved (Bastarrachea et al., 2015a; Chandrasekar et al., 2010). By controlling factors like the current density, bath composition, and deposition time, thin films with specific properties can be produced (Barish and Goddard, 2013). When zinc nanocrystalline coatings are deposited on steel substrates using pulse electrodeposition, they are less porous and more corrosion-resistant than direct current electrodeposition (Chandrasekar et al., 2010; Chen et al., 2021; Li et al., 2016). There have been reports that the corrosion resistance of nanocrystalline zinc on copper substrates varies significantly depending on the current density used (Chen et al., 2021). Electrochemical deposition is frequently utilized to create corrosion-resistant coatings. For example, applying a layer of zinc or chromium to a metal substrate can enhance its corrosion resistance (Chandrasekar

et al., 2010). Additionally, it can be used to create composite coatings by adding nanoparticles or organic molecules to the electrolyte solution (Li et al., 2016).

4. **Self-Assembly Processes**: Smart nanocoatings can be synthesized through self-assembly processes, which involve the spontaneous organization of molecules or nanoparticles into ordered structures without external intervention (Cao et al., 2022). These processes rely on non-covalent interactions like van der Waals forces or hydrogen bonding to assemble building blocks into functional nanocoatings (Sarode et al., 2020). The polyelectrolyte film can be sensitive to different physical and chemical conditions, like changes in pH or mechanical pressure from the environment, and the sensitivity allows for the controlled release of inhibitors trapped within the multilayers (del Mercato et al., 2014; Naqvi et al., 2023; Plazas-Tuttle et al., 2015). Typically, polyelectrolytes are assembled on the surface of nanoparticles using a layer-by-layer (LBL) approach to create nanocontainers loaded with inhibitors (Andreeva et al., 2010; de Villiers et al., 2011). The LBL assembly is a self-assembly process that deposits positively and negatively charged molecules or nanoparticles onto a substrate, forming a multilayer coating with tailored properties (Bastarrachea et al., 2015b). This technique incorporates functional components like enzymes, dyes, or nanoparticles into the coating structure (Mustafa and Andreescu, 2020). In addition to self-assembly processes, other techniques like chemical vapor deposition, sol-gel methods, and electrochemical deposition can also synthesize smart nanocoatings (Bastarrachea et al., 2015a). Each technique offers unique advantages and allows for coating synthesis with tailored properties and functionalities (Cao et al., 2022). These smart nanocoatings have many applications in various industries, including automotive, aerospace, electronics, energy, and healthcare (Singh et al., 2018).

CHARACTERIZATION TECHNIQUES

The different characterization techniques employed to analyze the properties of smart nanocoatings include scanning electron microscopy (SEM), atomic force microscopy (AFM), X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), and ellipsometry.

1. **Scanning Electron Microscopy (SEM):** Analyzing the morphology and structure of smart nanocoatings can be done with the help of SEM because it uses a focused beam of electrons to detect the images of the surface of materials with high resolution (Li et al., 2021; Singh et al., 2018). Through SEM, researchers can visualize nanoscale features of nanocoatings with precision

and observe nanoparticle size, shape, and distribution (Farooq et al., 2022). SEM also enables the examination of the porosity and roughness of the coating surface (Wadullah et al., 2022; Xia et al., 2020). Furthermore, the effects of wear and tear on the coating over time can be studied using SEM, providing valuable insights into the durability and stability of the material.

2. **Atomic Force Microscopy (AFM):** The AFM technique plays a crucial role in analyzing the properties of intelligent nanocoatings because it involves using a pointed tool to examine the surface of the coating, creating a 3D image of the material's terrain and mechanical traits (Dufrêne et al., 2017; Voigtländer, 2019). AFM helps researchers understand the coating's functional qualities by measuring its Young's modulus, adhesion strength, and friction coefficient (Dufrêne et al., 2017; Reggente et al., 2015). Furthermore, AFM can be used to study changes in the coating's surface properties after different or multiple exposures (Reggente et al., 2015; Voigtländer, 2019).
3. **X-ray Diffraction (XRD):** The XRD technique is highly versatile and helpful in analyzing smart nanocoatings' crystal structure and composition. XRD provides information about the arrangement of atoms within the material by measuring the intensity of X-ray reflections from the coating (Martinez et al., 2014; Noah, 2020; Xia et al., 2020). Through XRD, researchers can determine if any specific phases or defects are present in the coating, the degree of crystallinity, and the orientation of crystal grains (Bugnicourt et al., 2016; Xia et al., 2020). This information is crucial in understanding the coating's mechanical, thermal, and electrical properties (Li et al., 2021).
4. **Fourier-Transform Infrared Spectroscopy (FTIR):** The FTIR technique is a non-destructive way to analyze smart nanocoatings' molecular structure and composition and detect the infrared radiation absorption by the coating to gather information regarding the types of chemical bonds in the material (Kokate et al., 2013; Li et al., 2021). With FTIR, researchers can detect the presence of specific functional groups or molecules in the coating and determine the degree of cross-linking between them (Koslowski et al., 2018). This knowledge is essential for comprehending the chemical properties of the coating and its interactions with other materials (Wadullah et al., 2022).
5. **Ellipsometry:** It measures the polarization state of light reflected from the coating to provide data on the material's thickness, refractive index, and optical constants (Li et al., 2021; Petrik et al., 2020). Researchers use this method to determine the coating's optical properties across various wavelengths and angles, which helps understand its performance in various applications (Petrik et al., 2020; Wadullah et al., 2019). Moreover, ellipsometry can also observe how the coating's optical properties change after exposure to different environmental

conditions like temperature, humidity, or chemicals (Bugnicourt et al., 2016; Wadullah et al., 2019).

FUNCTIONALITIES AND APPLICATIONS OF SMART AND INTELLIGENT NANOCOATINGS

Nanocoatings have recently received much attention because of their distinct properties and potential applications. Among them, smart and intelligent nanocoatings have emerged as an encouraging technology with advanced features like self-healing, anti-fouling, anti-corrosion, anti-icing, and stimulus-responsive behavior (de Villiers et al., 2011; Khan et al., 2020; Xie et al., 2019). Nanocoatings consist of one or more molecular layers and can be applied to various materials such as metals, glass, ceramics, and polymers (Fig. 2) (Bastarrachea et al., 2015b; Cagri et al., 2004; Smirnova et al., 2012; Vasile, 2018). Certain nanocoatings are polymers that are either polymerized before or during application. "Smart coatings" offer a range of functions, including thermal insulation, controlled release of active ingredients, and self-healing capabilities (Vasile, 2018). They also provide additional features such as antimicrobial properties, wrinkle and stain resistance, hydrophobic and hydrophilic properties, UV protection, and antistatic properties, which contribute to the overall characteristics of the substrate material (Singh et al., 2018). These coatings can adjust to changes in their surroundings, which enhances their performance and lifespan (Abdel-Karim and Waheed, 2013).

1. **Self-Healing Nanocoatings:** These coatings incorporate healing agents like polymer chains or nanoparticles, which react when the coating is compromised and create a new layer that restores it to its original state (Sarode et al., 2020; Wei et al., 2015). Smart and intelligent nanocoatings have the crucial feature of self-healing, which means that the coating can repair itself automatically in case of damage or scratches (Shah et al., 2022; Vasile, 2018). This is made possible by specialized molecules that bond and fill in any cracks or gaps in the coating (Gu et al., 2020). Such nanocoatings have numerous potential uses, including protective coatings for bridges, buildings, vehicles, medical devices, and implants (Coyle et al., 2007). Self-healing nanocoatings contain microcapsules with healing agents that react when the coating is damaged (Vishwakarma, 2020), allowing it to repair itself without external assistance (Fig. 2). The coatings are ideal for situations where access is limited or frequent maintenance is impractical, such as protecting car exteriors from scratches or safeguarding aircraft surfaces from corrosion (Thakur and Kumar, 2022; Vishwakarma, 2020). Self-healing nanocoatings safeguard electronic devices

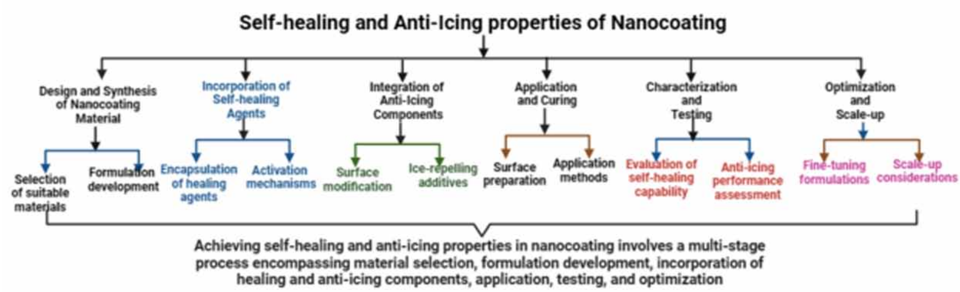
from harm and extend their longevity (Farooq et al., 2022; Idumah et al., 2020; Trentin et al., 2022). Additionally, they can enhance the efficiency and durability of solar panels by repairing surface damage. Nanocoatings with self-healing properties are revolutionary for enhancing durability across multiple industries (Kausar et al., 2023; Trentin et al., 2022). These coatings effectively safeguard building exteriors and infrastructure from damage, thereby minimizing the need for frequent repairs and maintenance (Kausar et al., 2023; Sadabadi et al., 2022). They have proven especially useful in the automotive, aerospace, electronics, energy, construction, and infrastructure industries (Kausar et al., 2023; Khan et al., 2020; Tang et al., 2023). Their unique ability to self-repair makes them an ideal option in situations where coated materials are hard to access or frequent maintenance could be more practical (Bastarrachea et al., 2015b; Idumah et al., 2020; Ortega-Nieto et al., 2023).

2. **Anti-Fouling Nanocoatings**: Nanocoatings for anti-fouling purposes are created to stop the accumulation of small organisms like bacteria and algae on surfaces (Nguyen-Tri et al., 2019). They can be used in several industries, such as aerospace, automotive, and healthcare, to protect against the growth of dangerous microorganisms (Barish and Goddard, 2013; de Villiers et al., 2011). Thin layers of anti-fouling nanocoatings can effectively prevent the accumulation of fouling substances on surfaces, providing benefits (Bhatt et al., 2015). These coatings can increase durability, decrease the need for maintenance, and minimize friction between surfaces (Zhou et al., 2022). Furthermore, they can improve fuel efficiency and corrosion resistance in marine applications while enhancing the resistance of devices and systems to biofouling (Abdeen et al., 2019). Anti-fouling nanocoatings find application in a broad spectrum of industries, including marine, medical devices, food processing, and water treatment. In marine industries, these coatings help enhance fuel efficiency, reduce maintenance costs, and extend the hull's lifespan (Zhou et al., 2022). In medical devices, nanocoatings prevent bacteria and other microorganisms from building up on devices like catheters and implants (Blum et al., 2015; Nguyen-Tri et al., 2019). The food processing industry uses anti-fouling nanocoatings to prevent the accumulation of bacteria and microorganisms on equipment and surfaces, enhancing food safety and minimizing contamination risks (Abdeen et al., 2019). Similarly, water treatment systems benefit from these coatings by preventing the buildup of fouling substances and improving the efficiency of the treatment process (Bhatt et al., 2015).
3. **Anti-Corrosion Nanocoatings**: Many industries face the challenge of corrosion-damaging surfaces, but anti-corrosion nanocoatings have been created to combat this issue. These special coatings safeguard metals such as steel and aluminum from corrosion, even in harsh surroundings. For instance,

two methods exist for creating intelligent coatings: directly adding inhibitors to the coating or encapsulating inhibitors in micro/nanocontainers distributed throughout the coating (Chen et al., 2023). The direct doping approach can cause problems like inhibitor leakage and interactions that harm the barrier properties of the coating (Wei et al., 2015). Adding inhibitors directly can also lead to the formation of electrolyte pathways and reduced barrier properties. Encapsulation of active materials in micro/nanocontainers that are compatible with the coating matrix and sensitive to local changes caused by corrosion can overcome these problems (Nazeer and Madkour, 2018). Additionally, incorporating nanoparticles into polymers can improve the durability of the coatings by filling cavities and reducing cracking (Khan et al., 2020). Also, nanocrystals embedded in a polymer matrix of corrosion-resistant materials like zinc oxide will prevent damage to surfaces by reacting with corrosive substances (Farag, 2020).

4. **Anti-Icing Nanocoatings**: Nanocoatings that prevent surfaces ice formation are called anti-icing nanocoatings, commonly utilized in cold climates to improve safety and performance in numerous industries, such as aerospace and automotive (Lin et al., 2018; Saini and Bhatt, 2020). This process is achieved by utilizing specific molecules that can lower the freezing point of water and prevent ice from forming on the coating's surface, even at freezing temperatures (Coyle et al., 2007). Anti-icing nanocoatings have numerous potential uses, such as on aircraft wings and control surfaces, wind turbines, other renewable energy systems, roofs, and gutters (Fig. 2) (Singh et al., 2023). It comprises a nanostructured surface that creates a slippery surface, making it challenging for ice to form and adhere to the surface (Lin et al., 2018; Xie et al., 2019). Furthermore, these coatings can prevent and release ice, lower maintenance needs, improve safety, increase energy efficiency, and may have environmental advantages (Xie et al., 2019). Transportation, infrastructure, renewable energy, marine, electronics, and healthcare sectors use anti-icing nanocoatings in practical applications (He and Guo, 2021; Lin et al., 2018; Xie et al., 2019)
5. **Stimuli-Responsive Nanocoatings**: Stimuli-responsive nanocoatings have gained popularity due to their adaptability and capacity to respond to environmental factors (Han et al., 2023; Plazas-Tuttle et al., 2015). They employ active ingredient release in a controlled manner according to specific stimuli, like pH or temperature, making them highly beneficial in many industries. They can be tailored to dispense drugs (Pham et al., 2020), antimicrobial agents, corrosion inhibitors, or other bioactive compounds in a targeted and localized fashion, ensuring precise delivery of therapeutic agents or safeguarding against corrosion (Plazas-Tuttle et al., 2015). Nanocoatings that respond to external

Figure 2. Self-healing and anti-icing properties of nanocoatings



stimuli are a game-changer due to their surface properties that can be altered from hydrophilic to hydrophobic, making them ideal for anti-fog coatings and self-cleaning surfaces (Cordeiro, 2011). Even nanocoatings that can change their optical properties, which has led to the creation of smart windows that optimize light transmission for energy-efficient buildings and vehicles (Plazas-Tuttle et al., 2015; Saha et al., 2021). Stimuli-responsive nanocoatings offer a wide range of applications across various industries. They can be utilized for drug delivery in biomedicine (Cabane et al., 2012; Pham et al., 2020), antibacterial coatings for medical devices (Blum et al., 2015), self-healing coatings for electronics, and anti-fogging and self-cleaning coatings in the automotive sector (Saha et al., 2021). Nanocoatings that are reactive to external factors have many uses in energy storage and conversion (Cordeiro, 2011). For instance, they can function as safeguarding coatings for batteries and fuel cells (Saha et al., 2021). Moreover, these coatings can enhance solar panel efficiency and may become more hydrophilic, which boosts its capacity to repel water and prevent the proliferation of microorganisms as the temperature increases.

Real-World Applications

Nanocoatings have many practical applications across various industries, providing distinctive features and advantages that make them suitable for specific uses. These coatings have the potential to enhance the effectiveness, longevity, and safety of different products and devices, and their usage is projected to expand. Smart and intelligent nanocoatings have numerous real-world applications in various industries, including:

i. **Aerospace**: self-healing, anti-icing, and stimuli-responsive nanocoatings can enhance aircraft and spacecraft performance and safety (Xie et al., 2019). Self-healing nanocoatings repair damaged surfaces, while anti-icing nanocoatings prevent ice formation on wings and other surfaces (He and Guo, 2021).

ii. **Automotive**: Anti-corrosion, anti-fouling, and stimuli-responsive nanocoatings influence the effectiveness of vehicles (Chen et al., 2023). For instance, anti-corrosion nanocoatings can safeguard car bodies from rust, while anti-fouling nanocoatings can prevent the build-up of microorganisms on surfaces (Zhou et al., 2022).

iii. **Electronics**: Nanocoatings that respond to stimuli can enhance the efficiency and dependability of electronic devices (Sathe et al., 2017). Temperature-sensitive nanocoatings can help regulate the heat of electronic devices, while humidity-sensitive nanocoatings can prevent the growth of microorganisms on surfaces.

iv. **Clothing**: Silica, silver, and titanium dioxide nanoparticles are frequently used to manufacture fabrics to deter moisture, eliminate bacteria, and inhibit creases. These beneficial properties make them popular for various clothing items, including raincoats, T-shirts, pants, and socks (Farooq et al., 2022).

v. **Healthcare**: Medical devices can benefit from nanocoatings that are anti-fouling, anti-icing, and stimulus-responsive (Blum et al., 2015). Anti-fouling nanocoatings prevent microorganism accumulation, while anti-icing nanocoatings prevent surface ice formation (He and Guo, 2021; Lin et al., 2018).

vi. **Food Industry**: Nanocoatings improves the taste and appearance of food, aiding in processing, and preventing harmful microorganisms from growing, which extends the shelf life (Bao et al., 2019). Additionally, it contributes to the development of safer packaging solutions, reduces the use of pesticides, and provides essential nutrients to crops. Food science has become increasingly reliant on nanotechnology and its benefits (Cui et al., 2023; Nile et al., 2020).

vii. **Energy**: Self-healing, anti-corrosion, and stimuli-responsive nanocoatings can enhance the performance and lifespan of energy-related infrastructure, including wind turbines and solar panels (Sathe et al., 2017). For instance, self-healing nanocoatings can fix damaged surfaces, while anti-corrosion nanocoatings can shield metal structures from corrosion (Saini and Bhatt, 2020).

viii. **Furniture**: Household furniture can be safeguarded from pests and fungi using silver, copper, and zinc nanoparticles and titanium dioxide particles to effective repel of dust and contaminants (Abdel-Karim and Waheed, 2013). Coatings that contain nanomaterials have the added benefit of extending furniture lifespan and reducing maintenance expenses. Furthermore, using carbon nanofibers can decrease upholstered furniture's flammability by as much as 35%

Smart and intelligent nanocoatings can transform numerous industries with advanced features. These coatings have the potential to enhance performance, safety, and durability while reducing maintenance expenses and environmental effects. As this technology progresses, we anticipate widespread implementation of these coatings in various applications.

CHALLENGES AND SOLUTIONS OF IMPLEMENTING NANOCOATINGS

Nanocoatings have gained significant attention recently due to their unique properties and potential applications in various industries. However, implementing these coatings on a large scale poses several challenges that must be addressed. This section will discuss the challenges and solutions of implementing nanocoatings in different industries.

1. **Scalability and Cost-Effectiveness**: Scaling up the production of nanocoatings poses a significant challenge in meeting the demands of industries. The cost of production and the requirement for large-scale manufacturing facilities are significant barriers to their widespread adoption. To overcome these challenges, developing cost-effective and scalable manufacturing processes is necessary.
2. **Toxicity and Environmental Impact**: Using nanomaterials in coatings has raised concerns about potential toxicity and environmental impact. One challenge is to ensure that nanocoatings are thoroughly tested and evaluated for their effects on human health and the environment before they can be widely adopt. It is important to address potential risks and ensure that nanocoatings are safe (Plazas-Tuttle et al., 2015).
3. **Interoperability and Standardization**: Ensuring the interoperability and compatibility of nanocoatings is a significant challenge due to varying specifications and requirements among manufacturers and industries. To address this, industry standards and specifications for nanocoatings need to be developed.
4. **Regulatory Framework**: The rules and regulations concerning nanocoatings are still developing, and there is a necessity for more guidance on their usage in various industries. Governments and regulatory agencies must collaborate to establish a comprehensive regulatory framework for safe, effective, and environmentally friendly.
5. **Public Awareness and Acceptance**: Increasing public knowledge and acceptance of nanocoatings is necessary. Some individuals must know these coatings' advantages and possible uses, resulting in limited usage. To overcome

this issue, we require more investment in educational and awareness initiatives that encourage the use of nanocoatings across various industries.

Despite facing some obstacles, the outlook for utilizing nanocoatings in multiple sectors appears promising. These coatings present many benefits, such as increased toughness, scratch resistance, and self-cleaning properties, rendering them an attractive option for various applications. Moving forward, we will delve into the potential implementation of nanocoatings across various industries.

EVALUATING THE PERFORMANCE OF SMART NANOCOATINGS

Smart nanocoatings are advanced materials that offer a range of properties and functions, such as self-healing, anti-microbial, and temperature-sensing capabilities. Evaluating the performance of these coatings is crucial to ensure their effectiveness and reliability in various applications. This section discusses the methodologies used to evaluate the performance of smart nanocoatings, including mechanical testing, adhesion testing, durability testing, and environmental stability assessment (Plazas-Tuttle et al., 2015). Additionally, standardized testing protocols are highlighted to ensure accurate and reliable results.

1. **Mechanical Testing**: Mechanical testing is essential to evaluate the physical properties of smart nanocoatings, such as their hardness, elasticity, and fracture toughness (Saha et al., 2021). These properties are critical in determining the coating's potential to sustain adverse effects and tear and its resistance to scratches and cracks. Standard mechanical testing methods include:
    i. Indentation testing: This method uses a sharp probe to indent the coating's surface and measure its resistance to deformation.
    ii. Scratch testing: This method involves scratching the coating's surface with a sharp object and measuring the depth and angle of the scratch.
    iii. Flexure testing: This method involves bending the coated surface to measure flexural strength and modulus.
    iv. Tensile testing: This method stretches the coated surface to measure its tensile strength and elongation.
2. **Adhesion Testing**: Adhesion testing is crucial to evaluating the bonding strength between the smart nanocoating and the substrate material. This testing is essential for applications where the coating must adhere to a specific surface, such as in medical devices or aerospace applications (Blum et al., 2015). Standard adhesion testing methods include:

   i. Peel testing: This method measures the force required to peel the coating off the substrate.
   ii. Shear testing: This method measures the force required to shear the coating of the substrate.
   iii. Adhesion testing using a scratch test involves scratching the coating's surface and measuring the force required to remove the scratch.
3. **Durability Testing**: Durability testing is essential to evaluating the long-term performance of smart nanocoatings under various environmental conditions. This testing is essential for applications where the coating must remain effective over an extended period, such as in construction or automotive applications. Standard durability testing methods include:
   i. Accelerated aging testing: This method involves exposing the coating to various environmental conditions, such as temperature, humidity, and UV radiation, to simulate the effects of aging (Bao et al., 2019).
   ii. Cyclic testing: This method involves subjecting the coating to repeated cycles of stress and strain to simulate real-world conditions.
   iii. Environmental stability assessment: This method involves evaluating the coating's stability under different environmental conditions, such as temperature, humidity, and chemical exposure (Plazas-Tuttle et al., 2015).
4. **Environmental Stability Assessment**: Environmental stability assessment is critical to evaluating the performance of smart nanocoatings under various environmental conditions. This testing is essential for applications where the coating must remain effective over an extended period, such as in construction or automotive applications. Standard environmental stability assessment methods include:
   i. Temperature testing: This method involves exposing the coating to different temperatures to evaluate its thermal stability.
   ii. Humidity testing: This method involves exposing the coating to different humidity levels to evaluate its resistance to moisture.
   iii. Chemical exposure testing: This method involves exposing the coating to different chemicals to evaluate its resistance to chemical corrosion

Importance of Standardized Testing Protocols

When evaluating smart nanocoatings, having standardized testing protocols in place is essential. These protocols help ensure that results are accurate and reliable while minimizing variability and ensuring the safety of testers and the environment. Testing methods like mechanical testing, adhesion testing, durability testing, and environmental stability assessment are all essential for evaluating the performance of these coatings. Manufacturers and researchers can use these methods and protocols to ensure that smart nanocoatings are effective and reliable, ultimately improving safety and performance in various applications.

COMPUTATIONAL MODELING AND SIMULATION TECHNIQUES IN STUDYING SMART NANOCOATINGS

Smart nanocoatings exhibit unique properties and functions, such as self-healing, adaptive behaviour, and responsiveness to environmental stimuli. Computational modelling and simulation techniques have played a crucial role in understanding the behaviour and performance of these nanocoatings at the molecular or atomic level. This part will explore the challenges and opportunities associated with computational approaches and highlight the benefits of using these tools to study smart nanocoatings.

Challenges and Opportunities of Computational Modeling

Smart nanocoatings pose a significant challenge in computational modeling due to their inherent complexity. These coatings consist of multiple layers of materials with varying properties and behaviors, with several factors affecting their functioning. Additionally, their molecular and atomic structures are susceptible to their surroundings, making it difficult to model their behavior precisely. However, despite these challenges, computational modeling and simulation techniques provide numerous opportunities for studying and understanding smart nanocoatings. These techniques allow researchers to:

- Design and optimize nanocoatings with specific properties and functions that can be used in simulations to test different material combinations and structures, identifying the most promising candidates for further experimentation.
- Study the behavior of nanocoatings under various stages, which can help researchers understand how the coatings respond to their environment and how they can be optimized for specific applications.
- Predict the performance of nanocoatings in different scenarios, such as exposure to chemicals or extreme temperatures, which can help manufacturers and engineers design and test coatings better suited for specific applications (Thakur and Kumar, 2022).
- Identify defects and weaknesses in nanocoatings, allowing researchers to develop strategies to improve their performance and longevity.

Benefits of Computational Modeling

Using computational modeling and simulation techniques to study smart nanocoatings has numerous benefits. Some of the key benefits include:

- Cost-effective way to study the behavior of nanocoatings, as it eliminates the need for expensive and time-consuming experiments.
- Fast and accurate methods allow researchers to study nanocoatings' behavior quickly under a wide range of conditions.
- Scalability is measured by scaling up or down to study the behavior of nanocoatings at different length scales, from the molecular to the macroscale.
- Insights into the material properties and behavior of nanocoatings at the molecular and atomic levels allow researchers to understand how the materials respond to their environment.

In conclusion, computational modeling and simulation techniques have proven crucial in understanding the behavior and capabilities of intelligent nanocoatings on a molecular or atomic level. These methods offer many possibilities, including designing and enhancing these coatings, comprehending their actions, predicting their performance, and identifying faults or vulnerabilities. The advantages of employing these techniques to investigate smart nanocoatings are numerous, such as cost-effectiveness, rapid and accurate results, scalability, and the acquisition of knowledge regarding material properties.

SMART AND INTELLIGENT NANOCOATING MARKET OPPORTUNITIES

The demand for advanced materials and technologies in various applications has rapidly expanded the market for smart and intelligent nanocoatings (Cui et al., 2023; Nile et al., 2020). According to reports by (Idumah et al., 2020; Thakur and Kumar, 2022), the global market for smart nanocoatings is projected to increase by 18.5% from 2020 to 2025, reaching $10.3 billion. This growth is driven by an increasing need for improved performance, durability, and sustainability in various applications that require advanced materials and technologies (Barhoum et al., 2019). The use of nanotechnology in industries like electronics, energy, and healthcare is also fueling demand for nanocoatings (Cui et al., 2023). Moreover, governments and companies invest heavily in research and development to develop new and improved nanocoatings with advanced properties. Additionally, the demand for surfaces that can self-heal or self-clean drives the smart and intelligent nanocoating market (Vijayan and Puglia, 2019).

The smart and intelligent nanocoatings market comprises three categories: type, application, and region (Akhila and Badwaik, 2022; Nguyen-Tri et al., 2019). The types of nanocoatings available are smart, intelligent, and hybrid, and they offer a range of benefits, such as sensing and communication capabilities, self-healing properties, and the ability to adapt to changing conditions (Barhoum et al., 2019). The market is divided around the globe, with many players striving to capture market share, and the competition is fierce. However, it is to be noted that some of the essential players include PPG Industries, Inc., AkzoNobel N.V., DuPont, Sherwin-Williams Company, Nippon Paint Holdings Co., Ltd., Jotun, RPM International Inc., Axalta Coating Systems, BASF SE, and Henkel AG & Co. KGaA. As technology advances, there is a growing emphasis on investing in research and development to make nanocoatings more accessible (Akhila and Badwaik, 2022). This has created lucrative market possibilities since nanocoatings have many applications, including construction, vehicles, defense equipment, airplanes, and boats. Thanks to extensive research and development, nanocoatings that are self-cleaning, water-resistant, and reduce friction have been developed (Ulaeto et al., 2019).

Conclusively, the smart and intelligent nanocoating market is experiencing rapid expansion, attributed to the increasing demand for advanced materials and technologies. This sector is categorized by type, application, and region and is highly competitive, with numerous significant players competing for a market share. As interest surges for surfaces that possess self-healing and self-cleaning properties, coupled with escalated investment in research and development, this industry is predicted to sustain growth in the future.

CRITICAL ANALYSIS OF EXISTING LITERATURE ON SMART AND INTELLIGENT NANOCOATINGS

In recent years, there has been a growing scientific interest in smart and intelligent nanocoatings because of their potential applications in various fields like energy, healthcare, and environmental protection. However, a thorough analysis of the existing literature has revealed gaps in knowledge, findings that need to be more consistent, and areas that require further research.

Gaps in Knowledge

- Lack of Standardization: There needs to be more standardization in the definition, synthesis, and characterization of smart and intelligent nanocoatings, which hinders the comparability and reproducibility of results across different studies (Ulaeto et al., 2019).

- Limited Understanding of Nanocoating-Substrate Interactions: The interactions between nanocoatings and substrate materials need to be better understood, which can affect the performance and stability of the nanocoatings.
- Insufficient Data on Toxicity and Environmental Impact: There is a need for more data on the toxicity and environmental impact of smart and intelligent nanocoatings, particularly in the long term.

Inconsistencies in Findings

- Variability in Nanocoating Properties: The properties of smart and intelligent nanocoatings can vary depending on the synthesis method, composition, and surface modification, leading to inconsistent results in different studies.
- Discrepancies in Characterization Techniques: Different characterization techniques can produce conflicting results, highlighting the need for standardized methods and protocols.
- Inconsistent Definition of Smart and Intelligent Nanocoatings: The terms "smart" and "intelligent" are often used interchangeably, but they have different meanings and implications for the properties and applications of nanocoatings.

Controversies and Debates

- Nanotoxicity: There is ongoing debate about the potential toxicity of nanomaterials, including nanocoatings, which can affect their use in various applications.
- Environmental Impact: The environmental impact of nanocoatings, especially their potential to leach or dispose needs further attention.
- Patent Issues: The patenting of nanocoating technologies can create controversy and hinder the development of new and improved coatings.

Different Perspectives

- Materials Science Perspective: Researchers from a materials science perspective may focus on the synthesis, characterization, and properties of nanocoatings while neglecting their potential applications and environmental impact.

- Application-Oriented Perspective: Application-oriented researchers may focus on the specific uses of nanocoatings, such as in energy or healthcare, without considering their broader implications and limitations.
- Environmental Perspective: Environmental researchers may focus on the potential environmental impact of nanocoatings, such as their disposal and leaching, without considering their potential benefits and applications.

In conclusion, while smart and intelligent nanocoatings have shown great promise in various fields, a critical analysis of the existing literature reveals several gaps in knowledge, inconsistencies in findings, and areas that require further research. Addressing these issues will be crucial for developing safe, effective, and sustainable nanocoatings for various applications

CONCLUSION AND FUTURE TRENDS

In conclusion, this book chapter provides a detailed overview of current research in the smart and intelligent nanocoatings where we emphasize the importance of this research and suggest new directions for further investigation. Developing smart and intelligent nanocoatings has significantly enhanced various industries' performance, durability, and safety. For instance, self-healing coatings could prolong the lifespan of structures and lower maintenance costs. Self-cleaning coatings could enhance solar panel efficiency and reduce water usage. Anti-icing coatings could make aircraft and cars safer during icing conditions. Sensing coatings could enable real-time monitoring of environmental conditions and structural health. The prospects for smart and intelligent nanocoatings also involve addressing scalability, cost-effectiveness, and regulatory compliance challenges. As research progresses, it is anticipated that advancements in manufacturing processes and formulation techniques will lead to commercializing these coatings on a larger scale, making them more accessible to various industries. Therefore, the authors recommend that future research focus on reducing costs and scaling up production as well as integrating smart and intelligent nanocoatings with existing technologies, such as sensors and actuators, to create more advanced systems. This could be achieved through the use of affordable materials or the development of new synthesis methods.

Funding: This study was funded by the Major Science and Technology projects of Henan Province (221100320200) and supported by Henan Center for Outstanding Overseas Scientists (No. GZS2021007).

REFERENCES

Abbasi, H., Antunes, M., & Velasco, J. I. (2020). Effects of Graphene Nanoplatelets and Cellular Structure on the Thermal Conductivity of Polysulfone Nanocomposite Foams. Polymers.

Abdeen, D. H., El Hachach, M., Koc, M., & Atieh, M. A. (2019). A Review on the Corrosion Behaviour of Nanocoatings on Metallic Substrates. Materials. doi:10.3390/ma12020210

Abdel-Karim, R., & Waheed, A. F. (2013). Nanocoatings. In Modern Surface Engineering Treatments. IntechOpen.

Abdulraheem, M. I., Zhang, W., Li, S., Moshayedi, A. J., Farooque, A. A., & Hu, J. (2023). Advancement of Remote Sensing for Soil Measurements and Applications: A Comprehensive Review. Sustainability. doi:10.3390/su152115444

Akhila, V., & Badwaik, L. S. (2022). Recent advancement in improvement of properties of polysaccharides and proteins based packaging film with added nanoparticles: A review. *International Journal of Biological Macromolecules*, *203*, 515–525. doi:10.1016/j.ijbiomac.2022.01.181 PMID:35122798

Andreeva, D. V., Skorb, E. V., & Shchukin, D. G. (2010). Layer-by-Layer Polyelectrolyte/Inhibitor Nanostructures for Metal Corrosion Protection. *ACS Applied Materials & Interfaces*, *2*(7), 1954–1962. doi:10.1021/am1002712

Ashfaq, A., Khursheed, N., Fatima, S., Anjum, Z., & Younis, K. (2022). Application of nanotechnology in food packaging: Pros and Cons. *Journal of Agriculture and Food Research*, *7*, 100270. doi:10.1016/j.jafr.2022.100270

Bao, W., Deng, Z., Zhang, S., Ji, Z., & Zhang, H. (2019). Next-Generation Composite Coating System: Nanocoating. *Frontiers in Materials*, 6.

Barhoum, A., Pal, K., Rahier, H., Uludag, H., Kim, I. S., & Bechelany, M. (2019). Nanofibers as new-generation materials: From spinning and nano-spinning fabrication techniques to emerging applications. *Applied Materials Today*, *17*, 1–35. doi:10.1016/j.apmt.2019.06.015

Barish, J. A., & Goddard, J. M. (2013). Anti-fouling surface modified stainless steel for food processing. *Food and Bioproducts Processing*, *91*(4), 352–361. doi:10.1016/j.fbp.2013.01.003

Bastarrachea, L. J., Denis-Rohr, A., & Goddard, J. M. (2015a). Antimicrobial food equipment coatings: Applications and challenges. *Annual Review of Food Science and Technology*, *6*(1), 97–118. doi:10.1146/annurev-food-022814-015453 PMID:25422880

Bastarrachea, L. J., Wong, D. E., Roman, M. J., Lin, Z., & Goddard, J. M. (2015b). Active Packaging Coatings. Coatings, 771-791. doi:10.3390/coatings5040771

Berger, L.-M. (2015). Application of hardmetals as thermal spray coatings. *International Journal of Refractory & Hard Metals*, *49*, 350–364. doi:10.1016/j.ijrmhm.2014.09.029

Bhatt, S., Pulpytel, J., & Arefi-Khonsari, F. (2015). *Low and atmospheric plasma polymerisation of nanocoatings for bio-applications*. Academic Press.

Blum, A. P., Kammeyer, J. K., Rush, A. M., Callmann, C. E., Hahn, M. E., & Gianneschi, N. C. (2015). Stimuli-Responsive Nanomaterials for Biomedical Applications. *Journal of the American Chemical Society*, *137*(6), 2140–2154. doi:10.1021/ja510147n PMID:25474531

Bugnicourt, E., Kehoe, T., Latorre, M., Serrano, C., Philippe, S., & Schmid, M. (2016). Recent Prospects in the Inline Monitoring of Nanocomposites and Nanocoatings by Optical Technologies. Nanomaterials. doi:10.3390/nano6080150

Cabane, E., Zhang, X., Langowska, K., Palivan, C. G., & Meier, W. (2012). Stimuli-Responsive Polymers and Their Applications in Nanomedicine. *Biointerphases*, *7*(1), 9. doi:10.1007/s13758-011-0009-3 PMID:22589052

Cagri, A., Ustunol, Z., & Ryser, E. T. (2004). Antimicrobial edible films and coatings. *Journal of Food Protection*, *67*(4), 833–848. doi:10.4315/0362-028X-67.4.833 PMID:15083740

Cao, L., Huang, Y., Parakhonskiy, B., & Skirtach, A. G. (2022). Nanoarchitectonics beyond perfect order–not quite perfect but quite useful. *Nanoscale*, *14*(43), 15964–16002. doi:10.1039/D2NR02537J PMID:36278502

Cerqueira, M. Â., Pinheiro, A. C., Ramos, O. L., Silva, H., Bourbon, A. I., & Vicente, A. A. (2017). Chapter Two - Advances in Food Nanotechnology. In R. Busquets (Ed.), *Emerging Nanotechnologies in Food Science* (pp. 11–38). Elsevier. doi:10.1016/B978-0-323-42980-1.00002-9

Chandrasekar, M. S., Shanmugasigamani, & Malathy, P. (2010). Synergetic effects of pulse constraints and additives in electrodeposition of nanocrystalline zinc: Corrosion, structural and textural characterization. *Materials Chemistry and Physics*, *124*(1), 516–528. doi:10.1016/j.matchemphys.2010.07.004

Chen, X., Chen, J., Zhu, J., Cai, T., & Guo, Z. (2021). Investigation on the Electrochemical Deposition of Nanocrystalline Zinc with Cationic Polyacrylamide (CPAM)-ZnSO(4) Electrolyte. *Micromachines*, 12. PMID:34577763

Chen, Z., Scharnagl, N., Zheludkevich, M. L., Ying, H., & Yang, W. (2023). Micro/nanocontainer-based intelligent coatings: Synthesis, performance and applications – A review. *Chemical Engineering Journal*, *451*, 138582. doi:10.1016/j.cej.2022.138582

Cordeiro, A. L. (2011). Stimuli-Responsive Polymer Nanocoatings. Nanotechnologies for the Life Sciences.

Coyle, S., Wu, Y., Lau, K.-T., De Rossi, D., Wallace, G., & Diamond, D. (2007). Smart Nanotextiles: A Review of Materials and Applications. *MRS Bulletin*, *32*(5), 434–442. doi:10.1557/mrs2007.67

Cui, H., You, Y., Cheng, G.-W., Lan, Z., Zou, K.-L., Mai, Q.-Y., Han, Y.-H., Chen, H., Zhao, Y.-Y., & Yu, G.-T. (2023). Advanced materials and technologies for oral diseases. *Science and Technology of Advanced Materials*, *24*(1), 2156257. doi:10.1080/14686996.2022.2156257 PMID:36632346

de Villiers, M. M., Otto, D. P., Strydom, S. J., & Lvov, Y. M. (2011). Introduction to nanocoatings produced by layer-by-layer (LbL) self-assembly. *Advanced Drug Delivery Reviews*, *63*(9), 701–715. doi:10.1016/j.addr.2011.05.011 PMID:21699936

del Mercato, L. L., Ferraro, M. M., Baldassarre, F., Mancarella, S., Greco, V., Rinaldi, R., & Leporatti, S. (2014). Biological applications of LbL multilayer capsules: From drug delivery to sensing. *Advances in Colloid and Interface Science*, *207*, 139–154. doi:10.1016/j.cis.2014.02.014 PMID:24625331

Dufrêne, Y. F., Ando, T., Garcia, R., Alsteens, D., Martinez-Martin, D., Engel, A., Gerber, C., & Müller, D. J. (2017). Imaging modes of atomic force microscopy for application in molecular and cell biology. *Nature Nanotechnology*, *12*(4), 295–307. doi:10.1038/nnano.2017.45 PMID:28383040

Farag, A.A. (2020). *Applications of nanomaterials in corrosion protection coatings and inhibitors*. Academic Press.

Farooq, S. A., Raina, A., Mohan, S., Arvind Singh, R., Jayalakshmi, S., & Irfan Ul Haq, M. (2022). Nanostructured Coatings: Review on Processing Techniques, Corrosion Behaviour and Tribological Performance. *Nanomaterials (Basel, Switzerland)*, *12*(8), 12. doi:10.3390/nano12081323 PMID:35458032

Girigoswami, A., Thirumalai, A., Karthick, H., Pallavi, P., Gowtham, P., & Girigoswami, A. (2022). Nanotechnology driven improvement of smart food packaging. *Materials Research Innovations*.

Gu, Y., Xia, K., Wu, D., Mou, J., & Zheng, S. (2020). Technical Characteristics and Wear-Resistant Mechanism of Nano Coatings: A Review. Coatings. doi:10.3390/coatings10030233

Han, J., Ma, Q., An, Y., Wu, F., Zhao, Y., Wu, G., & Wang, J. (2023). The current status of stimuli-responsive nanotechnologies on orthopedic titanium implant surfaces. *Journal of Nanobiotechnology*, *21*(1), 277. doi:10.1186/s12951-023-02017-8 PMID:37596638

He, H., & Guo, Z. (2021). Superhydrophobic materials used for anti-icing Theory, application, and development. *iScience*, *24*(11), 103357. doi:10.1016/j.isci.2021.103357 PMID:34825136

He, Q., Paiva, J. M., Kohlscheen, J., Beake, B. D., & Veldhuis, S. C. (2020). An integrative approach to coating/carbide substrate design of CVD and PVD coated cutting tools during the machining of austenitic stainless steel. *Ceramics International*, *46*(4), 5149–5158. doi:10.1016/j.ceramint.2019.10.259

Idumah, C. I., Obele, C. M., Emmanuel, E. O., & Hassan, A. (2020). Recently Emerging Nanotechnological Advancements in Polymer Nanocomposite Coatings for Anti-corrosion, Anti-fouling and Self-healing. *Surfaces and Interfaces*, *21*, 100734. doi:10.1016/j.surfin.2020.100734 PMID:34957345

Jagtiani, E. (2022). Advancements in nanotechnology for food science and industry. *Food Frontiers*, *3*(1), 56–82. doi:10.1002/fft2.104

Kausar, A., Ahmad, I., Maaza, M., & Bocchetta, P. (2023). *Self-Healing Nanocomposites&mdash*. Advancements and Aerospace Applications. In Journal of Composites Science.

Khan, S. A., Sezer, N., & Koç, M. (2020). Design, synthesis, and characterization of hybrid micro-nano surface coatings for enhanced heat transfer applications. *International Journal of Energy Research*, *44*(15), 12525–12534. doi:10.1002/er.5685

Kokate, M., Garadkar, K., & Gole, A. (2013). One pot synthesis of magnetite–silica nanocomposites: Applications as tags, entrapment matrix and in water purification. *Journal of Materials Chemistry. A, Materials for Energy and Sustainability*, *1*(6), 2022–2029. doi:10.1039/C2TA00951J

Koslowski, L. A. D., Nogueira, A. L., Licodiedoff, S., Comper, A. T., & Folgueras, M. V. (2018). Silver nanoparticles impregnated with polyamide-66 to disinfect drinking water. *Revista Ambiente & Água*, *13*(6), e1947. doi:10.4136/ambi-agua.1947

Li, C., Xia, F., Ma, C., & Li, Q. (2021). Research on the Corrosion Behavior of Ni-SiC Nanocoating Prepared Using a Jet Electrodeposition Technique. *Journal of Materials Engineering and Performance*, *30*(8), 6336–6344. doi:10.1007/s11665-021-05891-1

Li, M., Su, B., Zhou, B., Wang, H., & Meng, J. (2020). One-pot synthesis and self-assembly of anti-wear octadecyltrichlorosilane/silica nanoparticles composite films on silicon. *Applied Surface Science*, *508*, 145187. doi:10.1016/j.apsusc.2019.145187

Li, Q., Lu, H., Cui, J., An, M., & Li, D. (2016). Electrodeposition of nanocrystalline zinc on steel for enhanced resistance to corrosive wear. *Surface and Coatings Technology*, *304*, 567–573. doi:10.1016/j.surfcoat.2016.07.056

Li, T., Liu, Y., Liu, B., Guo, W., & Xu, L. (2017). Microstructure and Wear Behavior of FeCoCrNiMo0.2 High Entropy Coatings Prepared by Air Plasma Spray and the High Velocity Oxy-Fuel Spray Processes. Coatings.

Lin, Y., Chen, H., Wang, G., & Liu, A. (2018). Recent Progress in Preparation and Anti-Icing Applications of Superhydrophobic Coatings. Coatings. doi:10.3390/coatings8060208

Malik, S., Muhammad, K., & Waheed, Y. (2023). Nanotechnology: A Revolution in Modern Industry. *Molecules (Basel, Switzerland)*, 28. PMID:36677717

Martinez, G., Shutthanandan, V., Thevuthasan, S., Chessa, J. F., & Ramana, C. V. (2014). Effect of thickness on the structure, composition and properties of titanium nitride nano-coatings. *Ceramics International*, *40*(4), 5757–5764. doi:10.1016/j.ceramint.2013.11.014

Mohammed, M. T., & Hussein, S. M. (2019). Synthesis and characterization of nanocoatings derived by sol–gel onto a new surgical titanium surface. *Materials Research Express*, *6*(7), 076426. doi:10.1088/2053-1591/ab1722

Moncada, E., Quijada, R., & Retuert, J. (2007). Nanoparticles prepared by the sol–gel method and their use in the formation of nanocomposites with polypropylene. *Nanotechnology*, *18*(33), 335606. doi:10.1088/0957-4484/18/33/335606

More, S. R., Bhatt, D. V., & Menghani, J. V. (2017). Resent Research Status on Laser Cladding as Erosion Resistance Technique - An Overview. *Materials Today: Proceedings*, *4*(9), 9902–9908. doi:10.1016/j.matpr.2017.06.291

Motelica, L., Ficai, D., Oprea, O. C., Ficai, A., & Andronescu, E. (2020). Smart Food Packaging Designed by Nanotechnological and Drug Delivery Approaches. Coatings. doi:10.3390/coatings10090806

Mustafa, F., & Andreescu, S. (2020). Nanotechnology-based approaches for food sensing and packaging applications. *RSC Advances*, *10*(33), 19309–19336. doi:10.1039/D0RA01084G PMID:35515480

Naqvi, S. M. Z. A., Zhang, Y., Tahir, M. N., Ullah, Z., Ahmed, S., Wu, J., Raghavan, V., Abdulraheem, M. I., Ping, J., Hu, X., & Hu, J. (2023). Advanced strategies of the in-vivo plant hormone detection. *Trends in Analytical Chemistry*, *166*, 117186. doi:10.1016/j.trac.2023.117186

Nazeer, A. A., & Madkour, M. (2018). Potential use of smart coatings for corrosion protection of metals and alloys: A review. *Journal of Molecular Liquids*, *253*, 11–22. doi:10.1016/j.molliq.2018.01.027

Nguyen-Tri, P., Tran, H. N., Plamondon, C. O., Tuduri, L., Vo, D.-V. N., Nanda, S., Mishra, A., Chao, H.-P., & Bajpai, A. K. (2019). Recent progress in the preparation, properties and applications of superhydrophobic nano-based coatings and surfaces: A review. *Progress in Organic Coatings*, *132*, 235–256. doi:10.1016/j.porgcoat.2019.03.042

Nile, S. H., Baskar, V., Selvaraj, D., Nile, A., Xiao, J., & Kai, G. (2020). Nanotechnologies in Food Science: Applications, Recent Trends, and Future Perspectives. *Nano-Micro Letters*, *12*(1), 45. doi:10.1007/s40820-020-0383-9 PMID:34138283

Noah, N. M. (2020). Design and Synthesis of Nanostructured Materials for Sensor Applications. *Journal of Nanomaterials*, *2020*, 8855321. doi:10.1155/2020/8855321

Ortega-Nieto, C., Losada-Garcia, N., Pessela, B. C., Domingo-Calap, P., & Palomo, J. M. (2023). Design and Synthesis of Copper Nanobiomaterials with Antimicrobial Properties. *ACS Bio & Med Chem Au*, *3*(4), 349–358. doi:10.1021/acsbiomedchemau.2c00089 PMID:37599792

Petrik, P., Racz, A. S., & Menyhard, M. (2020). Complementary physicochemical analysis by ellipsometry and Auger spectroscopy of nano-sized protective coating layers. *Applied Surface Science*, *534*, 147593. doi:10.1016/j.apsusc.2020.147593

Pham, S. H., Choi, Y., & Choi, J. (2020). Stimuli-Responsive Nanomaterials for Application in Antitumor Therapy and Drug Delivery. *Pharmaceutics*, *12*(7), 12. doi:10.3390/pharmaceutics12070630 PMID:32635539

Plazas-Tuttle, J., Rowles, L. S., Chen, H., Bisesi, J. H., Sabo-Attwood, T., & Saleh, N. B. (2015). *Dynamism of Stimuli-Responsive Nanohybrids*. Environmental Implications. In Nanomaterials.

Prasad, S., Kumar, V., Kirubanandam, S., & Barhoum, A. (2018). Engineered nanomaterials: nanofabrication and surface functionalization. In A. Barhoum & A. S. H. Makhlouf (Eds.), *Emerging Applications of Nanoparticles and Architecture Nanostructures* (pp. 305–340). Elsevier. doi:10.1016/B978-0-323-51254-1.00011-7

Ramasubramanian, K., Arunachalam, N., & Ramachandra Rao, M. S. (2019). Wear performance of nano-engineered boron doped graded layer CVD diamond coated cutting tool for machining of Al-SiC MMC. *Wear*, *426-427*, 1536–1547. doi:10.1016/j.wear.2018.12.004

Reggente, M., Rossi, M., Angeloni, L., Tamburri, E., Lucci, M., Davoli, I., Terranova, M. L., & Passeri, D. (2015). Atomic Force Microscopy Techniques for Nanomechanical Characterization: A Polymeric Case Study. *Journal of the Minerals Metals & Materials Society*, *67*(4), 849–857. doi:10.1007/s11837-015-1340-9

Ros-Lis, J. V., & Benitez Serra, M. (2023). Recent advancements in smart and intelligent packaging technologies: an overview. In B. P. Singh, S. Agnihotri, G. Singh, & V. K. Gupta (Eds.), *Postharvest Management of Fresh Produce* (pp. 241–263). Academic Press. doi:10.1016/B978-0-323-91132-0.00010-1

Sadabadi, H., Allahkaram, S. R., Kordijazi, A., & Rohatgi, P. K. (2022). Self-healing Coatings Loaded by Nano/microcapsules: A Review. *Protection of Metals and Physical Chemistry of Surfaces*, *58*(2), 287–307. doi:10.1134/S2070205122020162

Saha, D. R., Kumar, K. R., Ansari, F., Ghosh, S. K., Datta, A., & Chakravorty, D. (2021). Stimuli-responsive coating by simple physical blending route. *Ceramics International*, *47*(18), 26357–26365. doi:10.1016/j.ceramint.2021.06.046

Saini, J., & Bhatt, R. (2020). Global warming-causes, impacts and mitigation strategies in agriculture. *Current Journal of Applied Science and Technology*, *39*, 93–107. doi:10.9734/cjast/2020/v39i730580

Sarode, A., Annapragada, A., Guo, J., & Mitragotri, S. (2020). Layered self-assemblies for controlled drug delivery: A translational overview. *Biomaterials*, *242*, 119929. doi:10.1016/j.biomaterials.2020.119929 PMID:32163750

Sathe, P., Laxman, K., Myint, M. T. Z., Dobretsov, S., Richter, J., & Dutta, J. (2017). Bioinspired nanocoatings for biofouling prevention by photocatalytic redox reactions. *Scientific Reports*, *7*(1), 3624. doi:10.1038/s41598-017-03636-6 PMID:28620218

Shah, M. A., Pirzada, B. M., Price, G., Shibiru, A. L., & Qurashi, A. (2022). Applications of nanotechnology in smart textile industry: A critical review. *Journal of Advanced Research*, *38*, 55–75. doi:10.1016/j.jare.2022.01.008 PMID:35572402

Sharma, C., Dhiman, R., Rokana, N., & Panwar, H. (2017). Nanotechnology: An Untapped Resource for Food Packaging. *Frontiers in Microbiology*, *8*, 8. doi:10.3389/fmicb.2017.01735 PMID:28955314

Singh, A., Mittal, S., Mudgal, D., & Gupta, P. (2018). Design, Development and Application of Nanocoatings. In Z. H. Khan (Ed.), *Nanomaterials and Their Applications* (pp. 191–207). Springer Singapore. doi:10.1007/978-981-10-6214-8_7

Singh, R., Dutt, S., Sharma, P., Sundramoorthy, A. K., Dubey, A., Singh, A., & Arya, S. (2023). Future of Nanotechnology in Food Industry: Challenges in Processing, Packaging, and Food Safety. *Global Challenges (Hoboken, NJ)*, *7*(4), 2200209. doi:10.1002/gch2.202200209 PMID:37020624

Smirnova, V. V., Krasnoiarova, O. V., Pridvorova, S. M., Zherdev, A. V., Gmoshinskiĭ, I. V., Kazydub, G. V., Popov, K. I., & Khotimchenko, S. A. (2012). Characterization of silver nanoparticles migration from package materials destined for contact with foods. *Voprosy Pitaniia*, *81*, 34–39. PMID:22774476

Sun, Z., Yang, L., Zhang, D., & Song, W. (2019). High performance, flexible and renewable nano-biocomposite artificial muscle based on mesoporous cellulose/ ionic liquid electrolyte membrane. *Sensors and Actuators. B, Chemical*, *283*, 579–589. doi:10.1016/j.snb.2018.12.073

Tang, K., Xue, J., Zhu, Y., & Wu, C. (2023). Design and synthesis of bioinspired nanomaterials for biomedical application. *WIREs Nanomedicine and Nanobiotechnology*.

Thakur, A., & Kumar, A. (2022). Self-healing nanocoatings for automotive application. In H. Song, T. A. Nguyen, G. Yasin, N. B. Singh, & R. K. Gupta (Eds.), *Nanotechnology in the Automotive Industry* (pp. 403–427). Elsevier. doi:10.1016/B978-0-323-90524-4.00019-0

Trentin, A., Uvida, M. C., de Araújo Almeida, A., de Souza, T. A. C., & Hammer, P. (2022). Self-healing nanocoatings. In H. Song, T. A. Nguyen, G. Yasin, N. B. Singh, & R. K. Gupta (Eds.), *Nanotechnology in the Automotive Industry* (pp. 371–401). Elsevier. doi:10.1016/B978-0-323-90524-4.00018-9

Ulaeto, S. B., Pancrecious, J. K., Rajan, T. P. D., & Pai, B. C. (2019). Smart Coatings. In S. Mohapatra, T. A. Nguyen, & P. Nguyen-Tri (Eds.), *Noble Metal-Metal Oxide Hybrid Nanoparticles* (pp. 341–372). Woodhead Publishing. doi:10.1016/B978-0-12-814134-2.00017-6

Vasile, C. (2018). *Polymeric Nanocomposites and Nanocoatings for Food Packaging: A Review*. Materials. doi:10.3390/ma11101834

Vijayan, P. P., & Puglia, D. (2019). Biomimetic multifunctional materials: A review. *Emergent Materials*, *2*(4), 391–415. doi:10.1007/s42247-019-00051-7

Vishwakarma, V. (2020). Synthesis, design, and characterization of controlled nanoparticles for the construction industry. In C. M. Hussain (Ed.), *Handbook of Nanomaterials for Manufacturing Applications* (pp. 323–341). Elsevier. doi:10.1016/B978-0-12-821381-0.00015-6

Voigtländer, B. (2019). Technical Aspects of Atomic Force Microscopy. In B. Voigtländer (Ed.), *Atomic Force Microscopy* (pp. 35–67). Springer International Publishing. doi:10.1007/978-3-030-13654-3_3

Wadullah, H. M., Ajeel, S. A., & Abbass, M. K. (2019). Synthesis and Characterization of Nanocoatings Thin films by Atomic Layer Deposition for Medical Applications. *IOP Conference Series. Materials Science and Engineering*, *518*(3), 032057. doi:10.1088/1757-899X/518/3/032057

Wadullah, H. M., Talib Mohammed, M., & Khalid Abdulrazzaq, T. (2022). Structure and characteristics of Nb2O5 nanocoating thin film for biomedical applications. *Materials Today: Proceedings*, *62*, 3076–3080. doi:10.1016/j.matpr.2022.03.229

Wei, H., Wang, Y., Guo, J., Shen, N. Z., Jiang, D., Zhang, X., Yan, X., Zhu, J., Wang, Q., Shao, L., Lin, H., Wei, S., & Guo, Z. (2015). Advanced micro/nanocapsules for self-healing smart anticorrosion coatings. *Journal of Materials Chemistry. A, Materials for Energy and Sustainability*, *3*(2), 469–480. doi:10.1039/C4TA04791E

Xia, F., Li, Q., Ma, C., & Guo, X. (2020). Preparation and characterization of Ni–AlN nanocoatings deposited by magnetic field assisted electrodeposition technique. *Ceramics International*, *46*(2), 2500–2509. doi:10.1016/j.ceramint.2019.09.244

Xie, Q., Hao, T., Zhang, J., Wang, C., Zhang, R., & Qi, H. (2019). Anti-Icing Performance of a Coating Based on Nano/Microsilica Particle-Filled Amino-Terminated PDMS-Modified Epoxy. Coatings.

Young, E., Mirosa, M., & Bremer, P. (2020). A Systematic Review of Consumer Perceptions of Smart Packaging Technologies for Food. *Frontiers in Sustainable Food Systems*, *4*, 63. doi:10.3389/fsufs.2020.00063

Zhou, Z., Pourhashem, S., Wang, Z., Duan, J., Zhang, R., & Hou, B. (2022). Distinctive roles of graphene oxide, ZnO quantum dots, and their nanohybrids in anti-corrosion and anti-fouling performance of waterborne epoxy coatings. *Chemical Engineering Journal*, *439*, 135765. doi:10.1016/j.cej.2022.135765