REVIEW

Surfactant Stabilized Nanoparticles for Environmental Sensing Applications

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Surfactants play a major role in the formation of nanoparticles due to their strong dispersion-enhancing properties. Nano-emulsions are non-equilibrium systems, their characteristics properties rely on both their synthesis process and composition. Research on optimization strategies for the synthesis of nanomaterials is currently increasing. Surfactants are a flexible class of materials that emphasize surface energy levels, chemical properties, regularity, pH sensitivity, activity and the performance of nanoparticles. The broad spectrum of surface improvements and applications, such as sensors, catalytic activity, the conversion of energy and storage capacity, biological acceptance and therapeutics, dispersion behaviour of nanoparticles in fundamental composite materials, cement, traditional detergents, purification systems and particular applications in environmental sensing have become inevitable. The exploration of design concepts for surfactants that enhance the efficacy of specific nanostructures has been increasingly prominent in recent discussions.

Keywords: Nanoparticles stabilization, Surface active agents, Detection, Biosensing, Environmental nanotechnology.

INTRODUCTION

In recent years, sustainable development has emerged as an important challenge. The long-term effects of environmental degradation on human health as well as the continued viability of both society and the economy, it persists as a formidable struggle. The pervasive presence of heavy metals, organic pollutants and environmental toxins from both natural and anthropogenic activities constitutes a pronounced environmental dilemma. Wastewater remediation, water purification, evoking substantial public and scientific concern [1-3].

Water represents a vital asset for all life forms but 1.1 billion individuals grapple with inadequate access to potable water [1]. Reusing wastewater becomes a practical solution to address this urgent issue. Pollutants generated by industries, agricultural sectors and other human activities include inorganic as well as organic substances [4]. Biosensors must be implemented for the continuous monitoring of air, water and the soil samples and identify various types of pollutants, including pesticides, potentially harmful elements, pathogens, poisons and organic substances that influence the endocrine system.

Fig. 1 illustrates the diverse biosensors utilized for the management, control and quantification of these pollutants [5]. Significant amounts of anionic surfactants (including LAS), phthalates, aromatic polycyclic hydrocarbons (PAHs), chlorinated biphenyls (PCBs), nonylphenol non-ionic surfactants such as coconut saturated fat diethanol amides (CDEAs), alkyl phenol ethoxylates (APEOs), alcoholic polyethoxylates (AEOs) and biochemical tin compounds have been detected as environment degrading organic pollutants. Heavy metals, fungicides, organochlorine insecticides and industrial chemicals such as biphenyls that are polychlorinated (PCBs) have been categorized into four major groups of persistent ecologically important toxicants. Despite their degradability, significant proportion of these surfactants traverse wastewater treatment plants and accumulate in sewage sludge due to their abundant presence in sources of wastewater and partial degradation that occurs during treatment [6]. Biological or synthetic elements with the ability to reversibly bind the analyte are combined with suitable chemical or mechanical sensors to develop specialized biosensors, which may effectively detect environmental contaminants. The specific pollutants found in given material can subsequen-

Biosensor

- **Advantages**
  - Non use of hazardous materials
  - Minimal sample pretreatment
  - Ease of use
  - Low cost
  - Smaller carbon footprints
  - Energy saving
- **Types**
  - Transducer
    - Mass-based biosensor
    - Thermal biosensor
    - Optical biosensor
    - Electrochemical biosensor
  - Bioreceptor
    - Microbial sensor
    - Genosensor
    - Aptasensor
    - Immunosensor
    - Enzymatic biosensor
- **Operation**
  - Pollutants
    - Signal processor
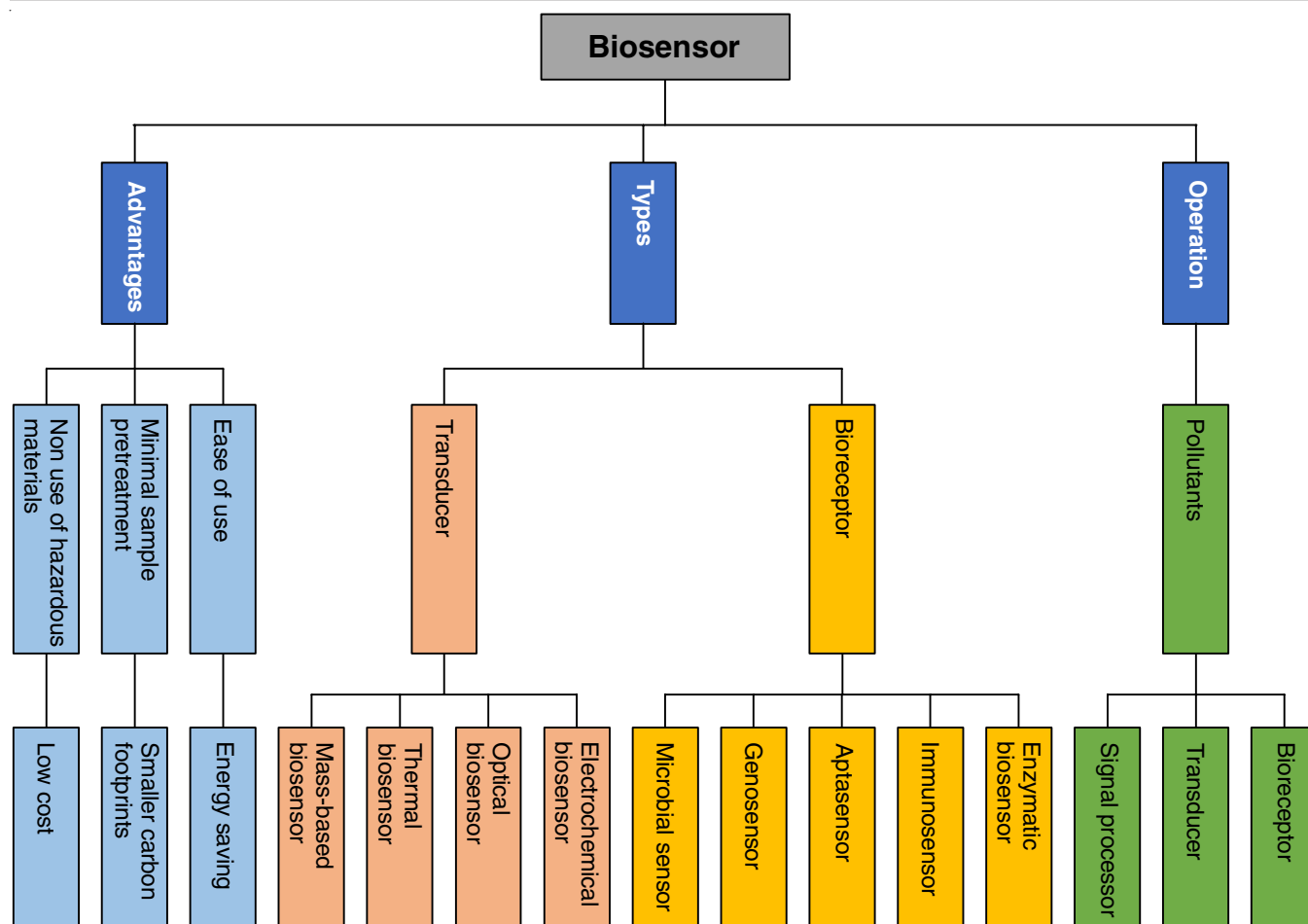   - Transducer
    - Bioreceptor

Fig. 1. Operation, types and advantages of biosensor

tly be more easily identified and translate the subsequent responses into quantitative as well as qualitative monitoring signals [7].

More than a billion people are predicted to live without access to clean water worldwide and in the next few decades, that number is expected to drop by a third. This review systematically delineates the realm of surfactant-coated nanoparticles across various sections *viz.* enhanced efficacy of nano confined sensors. Being versatile, their consequential applications in nanomedicine and nanoemulsions, along with their pivotal roles in industrial processes, cyclic voltammetry, environmental sensing applications. The contemporary advancements and challenges inherent in the utilization of surfactant-coated nanoparticles in environmental pollutants sensing applications have been discussed. This article covers an overview of surfactants, surfactant coated nanoparticles and their applications in environmental sensing. This review focuses on the utilization of nanoparticle sensors for the detection of chemical contaminants.

Nanosensors on effects and implications of pollutants: Heavy metals interact with DNA and nuclear proteins instigating site-specific damage. This damage can manifest in two distinct forms *viz.* direct and indirect. In cases of "direct" damage, the metal induces conformational alterations in the biomolecules [8]. Heavy metals can also cause "indirect" injury by generating reactive oxygen as well as nitrogen species. Moreover, research has demonstrated that heavy metals cause

transduction systems to light up [9]. Heavy metals are frequently concentrated in raw sewage, persisting through sewage treatment processes without degradation. Removal typically occurs in either the ultimate wastewater or the resulting muck. The nature and amount of contamination levels of sewage discharged into water bodies are contingent upon the sewage treatment processes employed. Addressing the issues arising from untreated sewage discharge into rivers and seas, stringent regulations have been implemented, coupled with advancements in technology aimed at reducing pollutant discharges into aquatic environments. These regulatory measures and technological innovations serve as critical controls to mitigate the adverse impacts of sewage contamination on water ecosystems [10-14].

Apart from the environmental, economic and societal ramifications associated with inadequate clean water [15-18], the availability of pure freshwater is essential for protecting health of the children and underprivileged [19,20]. Statistical estimates indicate that annually, 10-20 million death occur due to water-borne diseases, with nonfatal infections afflicting over 200 million individuals [21-23]. More than 0.78 billion people worldwide not having access to resources for safe drinking water [24].

Role of nanoparticles in environmental protection: Nanoparticles, typically between 1 and 100 nm in size, exhibit special

features which are not present in bulk materials. The domains of food nanoscale and nanomedicine are just two examples of the wide range of applications for surfactants as well as nanoparticles and surfactant-coated nanoparticles. Various synthesis methods are employed to fabricate nanomaterials, influencing their size, morphology and surface functionality (Fig. 2). The categorization of nanomaterials, synthesis methodologies, functionalization strategies, self-assembly mechanisms and detection techniques continue to expand in breadth and depth. Nanoparticles find applications across diverse domains, including electronics, magnetism, environmental remediation, pharmaceuticals, cosmetics, energy storage, opto-electronics, catalysis and materials science. Recently, the fields of biology, chemistry, physics and nanotechnology have come together to enable the development of extremely sensitive imaging and detection methods. Field applications in the areas of electricity, magnetism, the environment, medicine, cosmetics, energy, catalysis, optoelectronics and materials have resulted from these developments [25]. Significant progress has been made in the last 10 years in the use of nanoparticles as effective probes for environmental monitoring. Significantly in the analysis of heavy metal ions, organic toxins, organic gases, organic pesticides (such as Pb, Hg, As), inorganic pollutants, polychlorinated biphenyls and persistent dyes. The use of reverse osmosis (RO), micro filtering (MF), ultrafiltration (UF) and nanofiltration (NF), are examples of nano-enabled techniques used in wastewater remediation [26]. This is the most effective at eliminating pathogens, salts, minerals, cation, anions and overall dissolved solids (TDS). Significantly, nanofiltration also excels in pathogen removal, targeting viruses, protozoa and bacteria, thereby mitigating the risk of waterborne infections in both human and animal populations [27,28]. An investment of $6 billion is made annually in the US alone which is allocated towards nanotechnology research and development. Due to their huge difference between surface and volume ratio, nanoparticles can sense things quickly and with great sensitivity. Surface-modified micron-sized particles including carbon nanotubes, quantum dots (QDs that are) magnetic small particles (MNPs), gold as well as silver nanoparticles (AuNPs/AgNPs), demonstrate tailored surface functionalities enabling precise target recognition, facilitating

highly discerning and responsive target sensing capabilities [28].

Detection of chemical pollutants in water: The resistance of pathogenic microorganisms to traditional antibiotics presents a major obstacle to the general well-being. The widespread presence of such medicines in aquatic ecosystems has encouraged the study of remediation and very sensitive monitoring approaches. The environmentally safe development of nanoparticles, which could stop harmful chemicals and other biological materials from contaminating the environment [29]. Using versatile nanosorbents for the absorption and following identification of residual pollutants is a less-explored strategy [30]. Thus, nanoparticles hold promise for environmental sensing applications, in detecting extremely low concentrations pollutants. Utilizing nanomaterial has the benefit of concentrating pollutants to a degree that makes them detectable and removable. Using Au-TiO$_2$ NPs to concentrate and subsequently remove low quantities of pesticide from wastewater is one example of this [31]. Further research on efficient sensors that can detect nanosized contaminants is required.

Detection of heavy metals in water: Heavy metals contamination represents a formidable environmental challenge, posing a significant threat to global sustainability. As result, a lot of effort went into designing portable sensors to keep an eye on environmental heavy metal levels. However, most studies have merely shown prototypes for sensing that can detect heavy metals in solutions with buffers or synthetic materials. The application of sensors to challenging real-world materials for immediate, real-time metallic identification remains a significant obstacle. In addition to the problems listed below, these difficulties also include other problems. The presence of chemical and biological agents in common issue samples, such as urine, blood and river water, greatly impedes the capacity to identify signals. In certain situations, organic or inorganic fouling of the transducer causes the sensor to malfunction. The majority of the sensors that were previously disclosed could only identify heavy metals in their free ions. Unfortunately, a lot of heavy metals are present in metal-organic substances in samples rather than being free ions. When compared to conventional analytical approaches, sensors offer the benefits of porta-
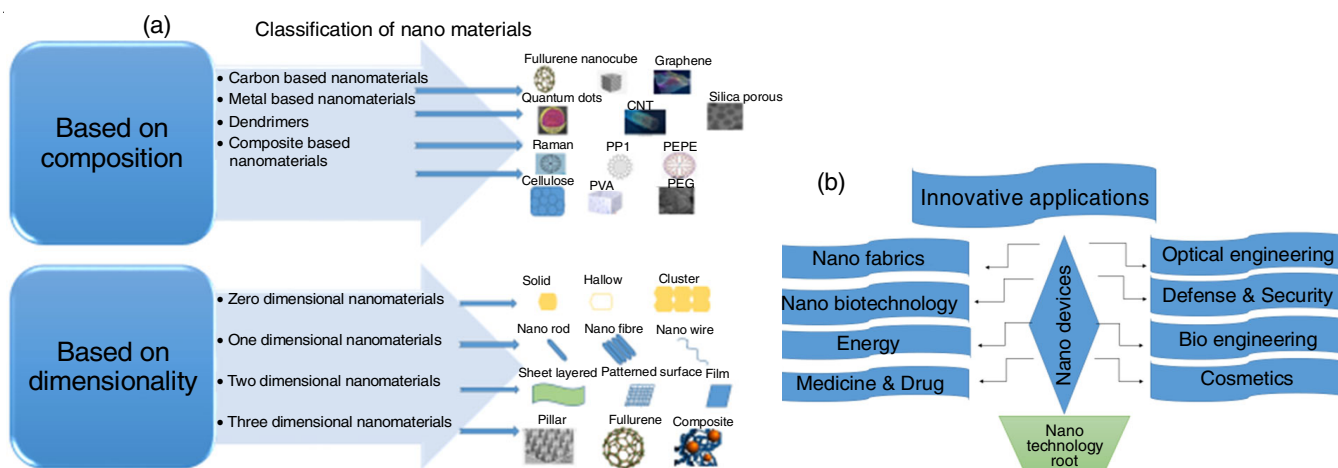

Fig. 2. (a) Classification of nanomaterials (b) innovative application of nanomaterials

bility and on-site detection [32]. Addressing these issues, creating LOC devices that combine microfluidics and sensors onto a single chip is a good idea. Metal-organic compounds can be broken down by the LOC chip's microfluidic module to release the free metallic ions and extract them from the sample matrix.

Nanoparticles in Covid 19 era: The COVID-19 pandemic has revealed the respiratory viral disease resistance deficiencies in human beings. Despite this, the biological immune system continues to be the major defense mechanism. However, individuals who are immune compromised or harbour underlying co-morbidities, such as hypertension and cardiovascular disorders, diabetes and other long-term disorders, are particularly susceptible [33]. For these vulnerable populations, their sole recourse lies in the utilization of masks for the face, immune system boosters, sanitizers and clinically approved pharmaceutical interventions [34]. The nanomaterials offer promising avenues for surface the oxidation process which releases harmful ions and prevents viral particles from binding and penetrating the surface to cause the virus to spread more slowly. This can be achieved through the production of heat-based photo thermal reactions and/or reactive oxygen species (ROS), which damage virus membranes.

These nanoparticles can be incorporated into surface coatings, textiles and personal protective equipment (PPE) to inhibit the persistence and spread of the virus that causes SARS-CoV-2 on the surfaces [35]. Their capacity to form oxygen species which are reactive and discharge hazardous ions upon interaction with moisture contributes to the inactivation of viral particles. Face masks incorporating nanoparticle-based coatings or filters offer enhanced protection against COVID-19 transmission. Nanoparticles like silver nanoparticles and graphene oxide nanoparticles, lipid based nanoparticles and polymeric nanoparticles serve as promising carriers for COVID-19 vaccines. Lipid based nanoparticles, in particular, have been employed for the delivery of vaccinations based on mRNA, including the Moderna and Pfizer and Bio COV-19 vaccines, quantum dots, magnetic nanoparticles and gold nanoparticles are utilized in various diagnostic platforms, including lateral flow assays and PCR-based assays [36]. Such nanoparticles make it possible to identify SARS-CoV-2 antigens of virus or nucleic acids with outstanding and sensitivity, which helps with fast diagnosis and COVID-19 outbreak control. Overall, nanoparticles offer versatile solutions for COVID-19 prevention by providing effective surface disinfection, enhancing mask filtration, enabling vaccine delivery and facilitating rapid diagnostic testing (Fig. 3). Their unique physico-chemical properties make them valuable tools in the global fight against the pandemic.
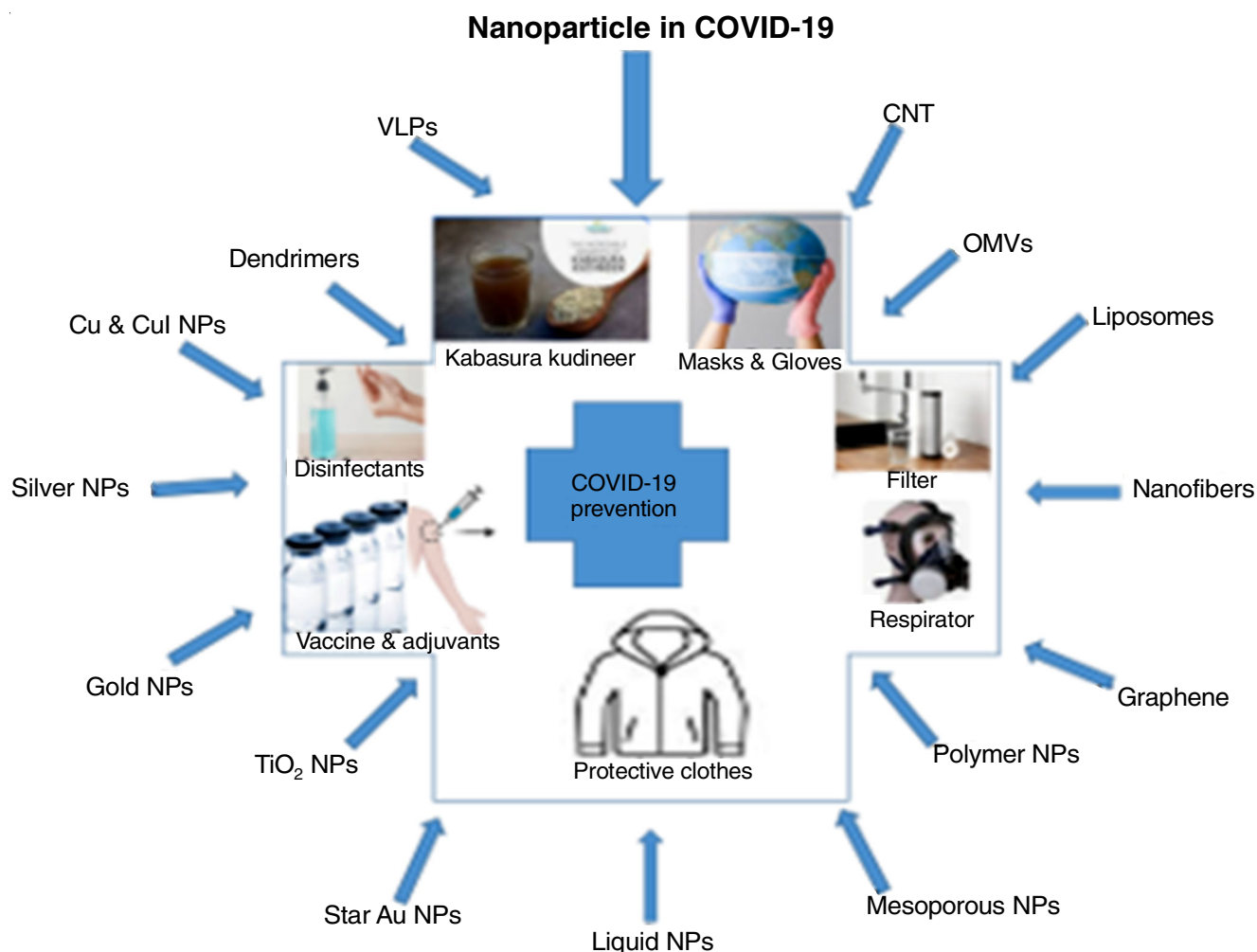
Nanoparticle in COVID-19

Fig. 3. Schematic representation of the nanomaterials used in COVID-19 prevention

The strong antibacterial qualities are exhibited by nano-technological surfactants, which inhibit the spread of microbes, algae, fungi and viruses. This ensures that nanoparticle-based medications are free from harmful microbes [37]. QD-functionalized nanorods composed of ZnO on gold paper electrodes showed the photoelectrochemical (PEC) approach offers potential for creating portable biosensors, improving transmission of charge, emission spectra and biocompatibility. The triple helix shape added to this PEC biosensor enhances its binding affinity and selectivity to HIV-DNA sequences [38]. The inkjet printed graphene-polyaniline (G-PANI) electrodes to create an eco-friendly electrochemical sensor for HPV viral detection. Thefunctionalization with AQ-PNA probes advances laboratory testing for viral diagnosis by enabling precise identi-fication of HPV genetic sequences with square-wave volta-mmetry [39]. A highly accurate luminescent biosensor for the hepatitis-18 detection was developed by utilizing dye-labelled ssDNA probes anchored in MXene Ti$_3$C$_2$ nanosheets. After attac-hing complementary HPV DNA, the sensor recovers its fluores-cence and the Exo III enzyme increases sensitivity to allow detection at concentrations as low as 100 pM [40].

Nanoparticles in other virus diseases: As the ebola spreads quickly and is very contagious, point-of-care (POC) technologies must take patient care into consideration. The novel multiplex lateral flow assay (LFA) devices are developed with AgNPs to detect dengue virus (DENV), yellow fever virus (YFV) than male and yellow fever virus simultaneously.They achieved this by taking advantage of the viruses' unique optical characteristics to differentiate distinct viral indicators using test line colour [41]. Zika virus (ZIKV) diagnosis was performed directly from whole blood samples using smartphone-integ-rated point-of-care testing (POCT) and antibodies coated with nanoparticles. Fast detection was made possible using Pt@Au core-shell nanostructures on a glassy chip, which is perfect for endemic areas with limited resources. On the other hand, early diagnosis is crucial for controlling the COVID-19 epid-emic. Therefore, all newly discovered corona viruses (CoV) particularly in elderly persons or those with co-occurring condi-tions, cause acute sickness and can be deadly in certain situa-tions, resulting in lung damage, multi-organ failure and heart failure) [42]. Nanobodies can be polymerized to increase avidity; dimeric Fc integration construct was developed for *in vitro* tests and neutralization studies, demonstrating additive effects when paired with CR3022 protein against new viral threats. In cases of severe COVID-19, this strategy backs the development of highly neutralizing agents and mixtures for passive immuni-zation [43].

Nanosensors: Nanomaterials have revolutionized sensor design by facilitating miniaturization, improving mobility and speeding up signal reaction times. Because of their easy surface functionalization and high surface area-to-volume ratios, nano-materials are remarkably sensitive to changes in surface chemistry, which makes it possible for nanosensors to attain incredibly low detection levels. Since nanomaterials are similar size-wise to the analytical substances of interest (such as metal ions, infections, biomolecules, antibodies and DNA) [44], it is sometimes assumed that the increased sensitivity of nano-

enabled sensors results from this. Three main signal transd-uction techniques are used by nano-enabled sensors *viz.* optical signals, electrochemical and electromagnetic. The optical tech-niques, especially colorimetric detectors operating within the visible spectrum, are favoured for widespread adoption among the broader population. Sensors can be tailored for the detection of a single analyte or multiple analytes, a capability known as multiplex detection. Additionally, a number of portable devices have been developed for nanoparticle based nanosensing, allowing for the high-sensitivity, multiplexed, quantitative and quick investigation of complex, raw materials. Nucleic acid customized nanoparticles based large-scale and ultra-sensitive techniques provide efficient screening techniques for a wide range of environmental analytes. Widespread uses of this techno-logy are anticipated in a number of industries, most remarkable environmental monitoring [45].

In recent decades, gold nanoparticles (GNPs) with diverse nano-structures have been extensively explored, owing to their large ratios of aspects, low dimensionality and related charact-eristics, which could lead to innovative uses in electronics, sensing and photonics. As an example, Cu^{2+} ions are visually detected in aqueous solutions using L-cysteine tailored golden nano-particles (GNPs). The colour of the GNP solution changes from red to blue when Cu^{2+} is present. With an efficiency of 10^{-5} M, this nanoparticles-based nanosensing allows for the quick and precise detection of Cu^{2+}. Among nanoparticles, GNPs and quan-tum dots (QDs) have a unique colour and fluorescence, they are frequently used as optical sensors [46]. When GNP aggre-gates consolidate or disperse, interparticle interactions cause GNPs to display a range of colours, from red to violet or blue. Moreover, some optical sensors use dyes or QDs changing in photoluminescence [28]. Because of their high signal-to-noise ratios, optical sensors are essential for identifying environ-mental contaminants. Table-1 listed the detection sensitivity of some gold nanoparticle based on sensing platform. Further-more, some sensor designs pre-concentrate the analyte using magnetic materials before using an optical or electrostatic transduction approach [47].

Efficacy of surfactant in nanosensors: The functionali-zation of nanoparticles to function as a barrier over the interior and its surroundings is influenced by surfactants. A layer of surfactant molecules that act as capping agents, immediately attaching to the surface to prevent the aggregation of the particles, scatter them in water at different pH levels and provide an ideal location for conjugation with active target molecules. To maxi-mize the effectiveness of a nanoparticle biosensor, the phase transition between the core of particles and its biological milieu is crucial and requires careful engineering [48]. The mechanisms underlying biosensing, which modulate nanoparticle signals upon interaction with analytes, are typically contingent based on interactions that vary with distance throughout the capping layer. Stronger signal modulation is typically elicited by thinner capping layers. These include resonance transfer of energy (RET), in which energy moves through space (usually up to 10 nm) through non-radiative dipole to dipole coupling and perturbation of the localized surface radiation (LSPR) field [65], in which molecules getting into the LSPR field change

Detection target	Sensor type	Sensitivity	Ref.
Heavy metal cations			
Pb^{2+}	Colorimetric sensor	3 nM	[48]
Hg^{2+}	Cation specific functionalized sensor	0.2 ppb	[49]
Divalent heavy metal ions	Direct electrostatic aggregation sensor	nM	[50]
Cu^{2+}	Electrochemical sensor	< 1 pM	[51]
Aromatic compounds			
2,4,6-trinitrotoluene (TNT)	Cysteine modified AuNP based	2 pM	[52]
Nitrobenzene	Electrochemical sensor	0.3 mg/L	[53]
Inorganic pollutants			
Nitrite ions	Cross linking colorimetric sensor	Sub-ppm	[54]
Nitrite ions	Non-cross linking colorimetric sensor	< 1 ppm	[55]
Nitrite ions	Electrochemical sensor	0.1 μm	[56]
Hypochlorite	Electrochemical sensor	1 μm	[57]
Arsenic	Electrochemical sensor	0.04 ppb	[58]
Organophosphate			
Organophosphate and phosphonates (OPPs)	Optical sensor	0.5 μm	[59]
OPP compounds/pesticides Toxins	Electrochemical sensor	0.1 nM	[60]
Ricin	AuNPs conjuncted with lateral flow strip assay		[61]
Ochratoxin A (OTA)	Immunochromatographic strip assay		[62-64]
Zearalenone (ZEA), aflatoxin B1			

the refractive index, which is the measurement of the sensing volume around a plasmonic nanoparticle (usually from 10 to 30 nm of surface). This imposes a requirement in the layer of capping, mandating to be both small and extremely protective. Hence, the range of surfactants includes conventional alkyl-based variations as well as peptides, fatty acids, DNA, polymer compounds, molecular ligands including bioconjugates that are engineered to modify surface properties. In the doubler emulsion process, for example, surfactants Tween and span and an organic solvent dichloromethane were utilized to evaporate a solvent that was used to develop the nanocapsules [66]. Minimal levels of both surfactants seem for resulting the larger burst release for penicillin-G loaded nanocapsules. Penicillin-G encapsulation can reach up to 60% under ideal formation conditions and because of the nanocapsules under 130 nm in diameter will be significant for burst release [66]. To prognosticate the influence of surfactants on the environmental dispersion and destiny of nano-TiO_2, it is imperative to scrutinize the compilation and sedimentation dynamics of titania nanoparticles within aquatic habitats. This endeavor aims to enhance the fidelity of simulations and deepen comprehension regarding how surfactants modulate the behaviours and transport mechanisms of TiO_2 engineered nanomaterials (ENMs) within a natural aqueous milieu, contrasting with the markedly distinct conditions prevailing in the ultra-pure Mille-Q water typically employed in laboratory settings [67].

The impact of surfactant hydrophobicity regarding large aspect ratio particles called nanorods shape control can be assessed by comparing different surfactants [68-70]. For instance, in case about 96% of the nanoparticles of gold in C_{10}TAB, which has a hydrocarbon chain that is the C_{10} atoms of carbon, have a spherical form with a factor 1, whereas only 4% appear to be short filaments with ratios of aspect ranging from two to three. Upon separation from the spherical structures, C_{12}TAB yields predominantly low aspect ratio nano rods, with approxi-

mately 92% displaying this morphology [71]. In contrast, C_{14}TAB results in gold nanorods with an aspect ratio of approximately 17, whereas C_{16}TAB produces nanorods with aspect ratio reaching up to 20. Thus, the length of the nanorods is evidently impacted by the alkyl chain length of the surfactant. The mechanism underlying production of micelles in the surfactants CTAB and SDS has been elucidated in myriad practical applications and products, surfactants assume critical roles as dispersants, emulsifiers, cleaners, wetting agents, foam enhancers and defoamers.

Role of surfactants in nanoshaping: Surfactants the amphiphiles, represent a ubiquitous class of chemical agents renowned for their remarkable cleansing efficacy, renders them indispensable across a multitude of industrial applications. Surfactant stabilized nanomaterials represent a significant advancement in nanotechnology, offering surfactants have stabilized the nanomaterials by adsorbing onto their surfaces, providing steric or electrostatic repulsion [72]. This prevents aggregation and maintains colloidal stability, which is essential for the applications requiring uniform dispersion. Surfactants can introduce functional groups that facilitate further chemical modifications, enhancing the versatility of nanomaterial for specific applications such as catalysis or biosensing. Achieving precise control over the resulting morphology entails strategically causing the head groups of surfactants to crosslink within reverse micelles through polymerization by free radicals [73-76]. Furthermore, amphiphilic surfactants have garnered attention as stabilizing agents facilitating creating stable dispersions of polar inorganic nanomaterial, such as graphene, carbon nanotubes (CNTs), transition metal containing dihalogenides and phosphorus [77]. Leveraging their distinctive molecular architecture, surfactants play a pivotal role in mitigating surface and interfacial tensions between multiple phases. Additionally, the propensity of surfactants to undergo self-assembly in solution engenders to the formation of micellar structures spanning a wide range of sizes, from nanometres to microns, further

amplifying their utility in dispersion science and technology [78].

Micelles: Surfactants have many essential characteristics, one of which is their ability to self-assemble into structures of nanoscale dimensions. Surfactant molecules organize themselves form micelles, which are nanometric structures, when their concentration surpasses the limit of their solubility [79,80]. Micelles are widely characterized as bulk phase-dispersed core-shell surfactant-based structures. Micelles can be arranged on flat sheets with many layers or in a spherical or cylindrical shape. Furthermore, the size and kind of the surfactant's hydrophobic tail, the polar head's characteristics, concentration, temperature, pH and other variables can all be changed to modify the micelle shape [81]. These micelles, emerge as a consequence of surfactant self-assembly, a phenomenon known as micellization process. These micellar architectures serve as effective templates for the synthesis of elongated nanostructures such as rods or wires [82].

Recent researches have shown novel nanostructures that are susceptible to reactive oxygen species. A prime example is a two-responsive micelle designed to deliver doxorubicin in addition to a cyclopalladated anti-tumor drug [83-91]. Recently, ethylene glycol-methyl poly(ester-thioether) micelles that are susceptible to ROS were formed; these micelles showed increased cellular absorption and strong anticancer effects. The miceller effect in intravenous administration of 1% nanocrystalline silver reduced the amounts of urine histamine, mast cell activation and renal neoplasm (TNF-α) without causing any negative side effects [92-96]. All things considered, these micelles showed exceptional efficacy and promise for the delivery of drugs and SPIO nanoparticles [62,97]. Zwitterionic groups such as sulfobetaines and carboxy betaines, feature a diversity of charges with a net neutral charge, ensuring stability over a wide pH and ionic strength range [98,99].

By comparing the sensing response of anionic and cationic surfactants, the cationic surfactant has been recognized for its effective sensing capabilities. The response of the sensor in absence of surfactant is recorded as 0.82, which escalates to 0.98 and 0.99 upon the inclusion of SDS and CTAB surfactants. According to Zhang *et al.* [100], an increased porosity and smaller crystallite size of the material may be the cause of this higher responsiveness in surfactant-assisted sensors. The surfactant-free sensor has a response time of 120 sec. But the response time drops to 70 and 30 sec, respectively, when CTAB and SDS were added. Notably, the lacking of sensor surfactant exhibits a modest recovery rate of only 58% within 500 sec. Moreover, the CTAB and SDS-assisted sensors demonstrated the efficient recoveries of 92% and 75%, respectively, within the same time period. As a result, the total recovery of sensing performance occurs only when utilizing SDS-coated samples, whereas without surfactant do not recover involving the CTAB-doped CuO sensor. With the CTAB-assisted sensor, the recovery time of sensor is somewhat longer. To enhance sensor recovery, heating to approximately 100 ℃ can be employed.

Surfactants in voltammetry sensors: Surfactants play a significant role across various applications in both electroanalysis and electrochemistry. Particularly in voltammetry, surfactants serve as modifying agents known to augment the selection and sensing process. These surfactants can be added to the electrode's composition and/or to the electrolyte solution. Frequently, in carbon-based electrodes in the experimental settings and adding a surfactant to the electrolytes to act as a modifying agent simplifies the method of electrode modification, referred to as *in situ* modification. This approach offers a crucial advantage by reducing or eliminating the need for extensive electrode preparation steps prior to investigation [101]. Furthermore, using differential pulse voltammetry (DPV), the presence of 1.0 mM CTAB was evaluated for thiosalicylic acid detection. The results showed a linear correlation range from 1 μM – 1 mM with a limit of detection of 0.11 μM [102].

Another DPV technique has shown bisphenol A (BPA) can be effectively determined in plastic items using an extended graphite paste electrode (DDAB-EGPE) modified by dodecyl derivated dimethyl ammonium bromide (DDAB). Based on acquired findings, the didodecyldimethyl ammonium bromide with electrode which contains graphite paste (DDAB-EGPE) exhibited superior enhancement of the electrochemical response towards BPA in comparison to the expanded graphite paste electrode (EGPE). This enhancement is primarily attributed to the pre-concentrating the BPA in DDAB due to the large surface area, increased conductivity and hydrophobic properties of expanded graphite [103].

Surfactants in electrochemical sensors: Electrochemical sensors represent a rapidly expanding field of study. Oxidation of metal nanoparticles can produce easily detectable ions using electrochemical means. Gooding *et al.* [104] pioneered the development of a detection limit of the electrolytic sensing of copper ions is less than 1 pM. Originally, gold nanoparticles were used to modify electrodes, followed by cysteine modification of the gold colloid surface for copper ion detection. Basic but effective biosensors have been developed by incorporating single-wall carbon nanotubes (SWNTs) into porous fibre materials such as textiles and papers [105]. Using SWNTs and antibodies, paper sensors were successfully developed for the effective and targeted detection of microscopic cysteine-LR (MC-LR). Wang *et al.* [106] achieved a detection limit of 0.6 ppb using a paper sensor for MCLR detection in Tai Lake water in China, which is comparable to enzyme-linked immune sorbent assays, yet provides an analysis time that is at least 28 times quicker. Similarly, Zhang *et al.* [100] functionalized single-walled graphite nanohorns with an analyte to detect MC-LR in Tai Lake water, resulting in the development of a sensitive electrochemical immune sensor. By utilizing MC-LR antibodies labelled with horse radish peroxidase in a competitive bioassay setup, the immunosensor exhibited a broad linear response ranging from 1 to 1000 ng/L, having a detection threshold of 0.06 ng/L [107]. With future development, the sensitivity of electrolytic sensing technologies could be expanded to enable on-site surveillance of hazardous elements in environmental matrices.

Factors affecting surfactant stabilized nanoparticles: The surfactant can stabilize nanoparticles, which are typically surface-active because of the amphiphilic groups present on their surface. The factors influencing stability include the dimensions, configuration and concentration of the nanoparticles,

in addition to the hydrophobic characteristics of the surfactants, as well as external conditions such as pressure, temperature, salinity, and humidity. The steric stability was strengthened by the surfactants placed at the solid interface by minimizing the agglomeration of nanoparticles [108]. For example, the adsorption and stabilization process of surfactants that are non-ionic on poly(lactic-*co*-glycolic acid) PLGA nanoparticles confirmed that when the two substances coexisted, a surfactant that was not ionic (poloxamer 188) with the adsorption of the surface on PLGA nanoparticles [109-113]. Moreover, the structural changes are possible with varying conditions including (i) the length and the morphology of surfactant, (ii) the degree of contact at the inorganic and organic interface and (iii) alkyl chain of surfactant [114].

Nanoparticle growth decreases upon the depletion of monomers or when nanoparticle surfaces achieve effective stabilization by surfactants [115]. For example, surfactant mediated growth pathways governing cobalt nanoparticles within a unified system, specifically, cobalt nanoparticles exhibit a diffusional growth trajectory when synthesized with trioctylphosphine oxide (TOPO) and oleic acid (OA), two surfactants, are present. Conversely, the coexistence of OA and dioctylamine (DOA) [48] induces the formation of multi-grained nanoparticles through an aggregation mechanism [116,117].

The genesis and manipulation of nanoparticle formation and morphology stand as pivotal for the fabrication of diverse nanomaterials, including semiconductor nanocrystals, metal nanocrystals and nanocomposites [118]. Thus, different regulated morphologies of nanoparticles have achieved through process routes, encompassing nanowires particles [119,120], nano-belts [121,122], nanotubes [123], nanocables, nanoflakes [124], nanoflowers [125,126], nanocubes [127,128], hollow nanospheres [129,130], core-shell structures [131-133] and diverse dimension-based particles especially 3D architectures [134,135]. Moreover, in the formation of various 1D t-Te nanoscale [136] investigations revealed the influence on nanoparticle formation and morphology control at higher micelle concentration (CMC at 1×10^{-2} M).

Applications of surfactant stabilized nanomaterials synergid: The surfactant stabilized nanomaterials are most applied for detection of chemical pollutants in environmental pollution, sensor in PAH control, environmental sensor and especially in nanomedicines. Ground-based measurements have traditionally been the primary method for monitoring urban pollution, while satellite data has remained largely untapped in environmental pollution assessment. High geographical and wavelength precision remote sensing technology have advanced, modelling urban pollution with satellite imagery is possible.

A. Surfactant based sensors in PAH control: The integration of modified electrodes with different types of surfactants has demonstrated remarkable electroanalytical characteristics, featuring a high surface-to-volume ratio and significant adsorption capacity. Within the domain of electrochemistry, there has been significant exploration into the role of surfactants due to their unique amphiphilic nature, characterized by a hydrophobic head and hydrophilic tail [137-142] such as Triton X-100 (non-ionic) [141] and another surfactant of anionic is sodium lauryl sulphate. Vittal *et al*. [142] employed cationic CTAB to quantify the compound nonylphenol on an electrode made of carbon paste (CPE) *via* cyclic voltammetry (CV). The results revealed that the adsorption of CTAB (both as monomer and as a bilayer) by the CPE surface rendered it positively charged and hydrophilic, impeding the accumulation of nonylphenol molecules characterized by high hydrophobicity and low solubility. Given that polycyclic aromatic hydrocarbons are known to be more environmentally toxic, it has been noted that in relation to anthraquinones, anthrones are especially poisonous, making them a significant concern in certain urban areas where they are prevalent as environmental contaminants, a modified carbon paste electrode featuring immobilized CTAB was also reported for the detection of anthrone (ANT), exhibiting an improved current response to ANT [143]. As this compound causes environmental toxicity issues as a pollutant due to the photooxidation process, which produces singlet oxygen and other reactive oxygen species ($^1O_2$), recognized for their adverse effects on pollutants and shown to be significantly harmful to mammalian cells [144,145].

B. Surfactant modified nanoparticles in enzymatic process: The advent of portable devices tailored for nanoparticle-based nanosensing has further expanded their utility. For instance, immune chromatographic strip assays, which offer visual readout capabilities, can be employed for rapid screening. However, the quantification of analytes typically requires specialized instrumentation such as an array scanner or equivalent. A noteworthy application of gold nanoparticles (AuNPs) involves their utilization in the organophosphorous pesticide detection using colorimetric methods. Acetyl cholinesterase (AChE)-catalyzed enzymatic hydrolysis reaction and AuNPs dissolution in Au31 or CTAB are the two key components of this detection technique [146]. AuNPs can be hydrolyzed by a mild oxidizing in the presence of cationic CTAB, which is a unique mechanism that results in a noticeable colour change from red to colourless. In this case, acetyl thiocholine, the enzymatic substrate, is transformed by AChE and the resulting thiocholine protects AuNPs from dissolution. On the other hand, when an inhibitor is present, the enzymatic activity is slowed down, which causes AuNPs to oxidise to Au31/CTAB and change colour of pink from red or colourless. A model inhibitor known as parathion was detected under ideal conditions with a limit of detection as low as 0.7 ppb and the stability of the procedure was unaffected by the addition of a modest amount of salt (5 mM NaCl). In addition, the use of gold nanoparticles is considered as "gold standard" by the development of immune assays laterally [147]. The anionic sodium dodecyl sulfate (SDS) surfactant was introduced into an electrolytic solution containing sodium rabeprazole (RAB sodium) and its effect on the response voltammetrically was investigated using a pencil graphite electrode (PGE). The findings indicated that the presence of 45 μM SDS led to an enhancement in the oxidation peak current. Utilizing CV technique for analysis, a range spanning from 0.5 to 250 μM was established, with a limit of detection of 0.18 μM. The mechanism underlying this enhancement involves the protonation of nitrogen groups in a compound called benzimidazole and RAB sodium

pyridine rings, which results in the production of cationic species at pH 6. SDS is then adsorbed onto the electrode surface, enabling easy access for RAB sodium in the surface of electrode [100]. RAB sodium has been effectively found in urine samples using this approach. In a related study, an SDS-based sensor with excellent sensitivity for the measurement of catechol and resorcinol was aslo reported using a modified by the electrode with graphene paste (GPE) [148].

Surfactant-coated nanoparticles in nanomedicines: Innovative materials and substitutes for phospholipid-based nanostructures can take advantage of the affordability, remarkable stability, minimal toxicity and dual affinity of non-ionic surfactants. Recent progress in this field is summarized in Table-2. Exploiting the synergistic effects of nanoparticles and surfactants could lead to innovative solutions, but problems remain, such as safety concerns.

TABLE-2
SURFACTANT STABILIZED NANOMATERIALS IN NANOMEDICINE

Surfactant coated nanoparticles	Applications	Ref.
PLGA nanoparticles encapsulating plasmid DNA covered with cationic surfactant [DDAB])	Transfection efficiency into murine macrophage (RAW 264.7) cells, increase in cellular uptake and endosomal escape transfection was achieved with a one thousandth amount of plasmid DNA	[149]
RNA [siRNA] encapsulated in solid lipid nanoparticles coated with a cationic surfactant [1,2-dioleoyl-3-trimethylammonium-propane (DOTAP	The activation of the innate immune system in C57BL/6 mice. 10- to 75-fold higher induction of type 1 helper (Th1) cytokine expression than the control particles (weakly onic charged	[150]
PLGA nanoparticles coexisted with nonionic polymers (polyethylene glycol [PEG]) and cationic surfactant (DDAB	Actively involved in the phagocytosis of macrophages in the spleen, bone marrow and liver	[151]
Silver nanoparticles coated with nonionic surfactants, such as poloxamers	As a targeting ligand for receptor on cancer cells and reported that the opsonized form of these nanoparticles lost their targeting ability. Avoid opsonization for effective targeting ability of nanoparticles *in vivo* and to reach the target site of action	[152]
PEG modification of nanoparticle	An immune response-induced mechanism to remove PEG-modified nanoparticles from the body	[153]
Nonionic surfactants (pluronic PE6100, PE6400 and PE6800) on hydrophobic interfaces (blend film composed of polylactic acid [PLA] and PLGA)	Adsorb and distribute effectively to the hydrophobic interface Solid interface increased steric stabilization.	[154]
Nonionic surfactants on PLGA nanoparticles and confirmed that a nonionic surfactant (poloxamer 188)	On the surface of PLGA nanoparticles increased, the steric stability of nanoparticles was greatly increased The stabilization by the repulsive hydration force is unaffected by the external salt concentration,	[155]
Poly(methyl methacrylate) nanoparticles was stabilized in non- polar solvents (hexane) when a nonionic surfactant (sorbitan trioleate, also named as Span 85)	Increase in inhibition of aggregation and stabilization of dispersion in a concentration-dependent manner	[156]
Anionic surfactant (SDS); nonionic surfactant (poloxamers)	Little effect on the release rate of the encapsulated drug from the solid dispersions.	[157]
PLGA nano/micro particles encapsulating lipophilic substances (perfluorooctyl bromide [PBOB]) by the three different Anionic surfactants (PVA, sodium cholate [SC] [Fig. 1], sodium taurocholate [TC], [Fig. 1])	Particle formation and particles with a core-shell shaped morphology were stably deposited in the system	[158]
Iron-encapsulated PLGA nanoparticles by optimizing the surface modification with a nonionic surfactant (poloxamer 188)	No cellular uptake of surfactant-coated nanoparticles after 1 h of incubation.	[159]
Retinoic hydroxamic acid coated with nonionic surfactants (poloxamer 184 and 188)	Enhanced anticancer activity due to increased accumulation in cancer cells and decreased accumulation in the liver during the 16 h observation period, compared to bare nanoparticles	[160]
Gold nanoparticles covered with a nonionic surfactant [polysorbate 80]	Adsorption of opsonization-related substances (bovine serum albumin [BSA], fibrinogen, γ-globulins, immunoglobulin G [IgG] and lysozyme) on surfactant-coated nanoparticles in phosphate buffer was inhibited and no aggregation was observed for 24 h.	[161]
Polystyrene nanoparticles covered with a nonionic surfactant [poloxamer 188]	Adhesion of IgG on the surface of surfactant-coated nanoparticles and 80% of the surface area was covered by IgG Suppression of opsonization is not due to adhesion but due to conformational changes in IgG	[162]
Zein and PLGA nanoparticles encapsulating lipophilic flavonoid (rutin) with sodium deoxycholate monohydrate (SD)	Interaction between rutin and zein exhibited longer drug release kinetics in the zein group compared to the PLGA group	[163]
Rivastigmine-encapsulated PBCA nanoparticles coated with polysorbate 80	Quantitatively evaluated their transport to the brain Four-fold increase in the concentration of rivastigmine in the brain 1 h after administration compared to the group receiving free drug.	[164]
Coumarin-6 encapsulated PLGA nanoparticles coated with polysorbate 80	Two-fold increase in the concentration of coumarin-6 in the brain 1 h after administration, compared to a group of rats being administered bare nanoparticles (without surfactant coating)	[165]

PLGA nanoparticles encapsulated with β-carotene and coated with polysorbate 80	Higher drug accumulation in the lungs (350-fold higher concentration compared to the group of bare nanoparticles) than in the brain after 1 h of administration.	[166]
Polymethyl methacrylate resin nanoparticles coated with various nonionic surfactants (polysorbates [20, 60 and 80], poloxamers [184, 188, 338, 407 and 908] and polyoxyethylene lauryl ether [Brij 35]	11-Fold increase in accumulation in the lungs and a nine-fold increase in accumulation in the brain after 30 min of administration	[167]
PLGA nanoparticles encapsulated with recombinant human erythropoietin [rhEPO] and coated with sodium cholate or polysorbate 80	Evaluated their cellular uptake (human neuroblastoma [SH-SY5Y] cells) and evaluated inhibition rate of glutamate-induced neurotoxicity.	[168]
Mesoporous silica nanoparticles coated with non ionic ethylene-bridged silsesquioxane	Tabilize the skeletal structure and to inhibit the exposure of silanol groups, resulting in decreased hemolysis from 10% to a few percent and further stabilized the skeletal structure	[169]
Mesoporous silica nanoparticles with doxorubicin encapsulating with polystyrene sulfonate	Successfully released both the drugs according to the pH and redox status of the cancer cells in vitro	[170]
Carbon nanoparticles coated with SDS	Interact with platelets and vascular endothelial cells, resulting in localized inflammation *in vivo*.	[171]
Polystyrene nanoparticles coated with a hydrophilic polymer (PEG)	The small intestinal villi with a homogeneous distribution.	[172]
Polystyrene nanoparticles encapsulating with nonionic surfactant (poloxamer 407)	Uniformly dispersion in the mucus while maintaining the barrier function of the mucus to herpes simplex virus type-1 (HSV-1)	[173]
PLGA nanoparticles enhancedcationic surfactant (SDS) and nonionic surfactants (poloxamers [188, 407], polysorbate 80	To inhibit the interaction between the core of particles and mucus components	[174]
Poloxamer 407-coated fluorescently tagged PLGA nanoparticles	60–80% of the surfactant-coated nanoparticles were dispersed in the mucus layer by coating with poloxamer 407, regardless of the type of nanoparticles	[175]
Gum arabic containing silver nanoparticles and a nonionic surfactant (glyceryl monostearate	Protected the antioxidant (vitamin C) in the green bell pepper from dehydration and microbial spoilage and maintained marketable quality even after 21-days of storage	[176]
Silver nanoparticles coated with SDS or polysorbate 80	Increased antimicrobial activity of silver against 10 strains of bacteria	[177]

Surfactant modified nanoparticles as softening agent: Flexible zwitterionic ligands, which give nanoparticles exceptional functionality and stability [178]. These zwitterionic ligands form hydrogen bonds and electrostatic interactions have the capacity to bind numerous water molecules, thereby constraining non-specific relationships to biomolecules in the environment. This is important as nanoparticles exhibit an inherent tendency to absorb biomolecules such as proteins, leading to the formation of a "corona" that if excessively dense or firmly bound, can impede analyte access to biosensing mechanisms attached to surfaces [179].

Surfactants, sodium dodecyl sulfate (SDS) and trimethyl-cetylammonium bromide (CTAB), are widely utilized in textile softening agents, detergents and industrial goods. CTAB is additionally utilized in increased oil recovery [180,181]. It has also been utilized to facilitate foaming for the extraction of proteins and enzymes [182,183]. Thus, foam can be made more robust through the combination of nanoparticles and surfactants. Research has been conducted on the stability of aqueous foams using the combination of CTAB and nanoparticles. Shojaei *et al.* [184] investigated the effects of surfactants with different charges (anionic, cationic, and non-ionic) on foam stability in the presence of charge-stabilized silica (SiO$_2$) nanoparticles. A network of nanoparticles improves stability by forming dense solid layers that more efficiently prevent film thinning and gas diffusion, thus elevating the viscosity of the surfactant solution and decreasing gas diffusivity. Research has shown that nanoparticles, irrespective of their characteristics (type and nature), play a crucial role in influencing both the static and dynamic

stabilities of foam [185]. A recent modeling study suggests combining nanoparticle transport models with conventional foam models to evaluate the flow process of foam stabilized by nanoparticles in porous media. The prompt implementation of foams stabilized by nanoparticles could face challenges due to issues like the clumping of nanoparticles, doubts about economic feasibility, and worries regarding health and environmental impacts [186].

Conclusion

The utilization of surfactant modified nanoparticles has underscored the pivotal role of surfactants in various fields. Surfactants play a ubiquitous role in various industries and households and hold potential for detecting wastewater with high concentrations. The synergistic interactions between the nanoparticles and surfactants can facilitate the development of various important technologies; nevertheless, safety concerns must be addressed. This review attempts to organize the extensive literature related to the applications of surfactant-stabilized nanoparticles by providing essential insights into their principles, fabrication methods and sensing properties. Scaling up the production of surfactant-stabilized nanoparticles while maintaining uniform quality and performance presents significant challenges. Thus, understanding and mitigating the environmental impact of surfactant-stabilized nanoparticles is essential to ensure their safe application.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

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