UNIVERSITI MALAYSIA PERLIS

International Journal of Nanoelectronics and Materials

IJNeaM

ISSN 1985-5761 | E-ISSN 2232-1535

Sensors for Polystyrene Nanoplastics Detection in Water Samples

Nurul Iman Ramzan[a], Mohamad Faris Mohamad Fathil[a,*], Mohd Khairuddin Md Arshad[a,b], Mohammad Nuzaihan Md Nor[a], Liu Wei Wen[a], Shahidah Arina Shamsuddin[a,c], Nur Hamidah Abdul Halim[a], Jasni Mohamed Ismail[a], Mohd Isa Ahmad Azan[a], Mohamad Izha Ishak[d], Siti Fatimah Abd Rahman[e], and Rajapaksha Dewage Asanka Amith Rajapaksha[f]

[a]*Institute of Nano Electronic Engineering, Universiti Malaysia Perlis, 01000 Kangar, Perlis, Malaysia*
[b]*Faculty of Electronic Engineering & Technology, Universiti Malaysia Perlis, 02600 Arau, Perlis, Malaysia*
[c]*Faculty of Mechanical Engineering & Technology, Universiti Malaysia Perlis, 02600 Arau, Perlis, Malaysia*
[d]*Industrial Centre of Innovation in Energy Management, Advanced Materials Research Centre (AMREC), SIRIM Berhad, 09000 Kulim, Kedah, Malaysia*
[e]*School of Electrical and Electronic Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Penang, Malaysia*
[f]*Department of Nano Science Technology, Faculty of Technology, Wayamba University of Sri Lanka, 60200 Kuliyapitiya, Sri Lanka*
**Corresponding author. e-mail: mohamadfaris@unimap.edu.my*

Received 15 September 2023, Revised 1 October 2025, Accepted 27 October 2025

ABSTRACT

Polystyrene nanoplastics (PS-NPs) are increasingly discovered in aquatic ecosystems, posing ecological and human health problems. Identifying PS-NPs in complex environmental matrices remains difficult due to their small dimension, chemical passiveness, and the existence of background interferences. Recent improvements in sensor and biosensor technologies have shown promise for improving the sensitivity, selectivity and portability of PS-NPs detection systems. However, maintaining high detection accuracy while minimizing false signals and matrix interferences remains a significant challenge. Limited selectivity, sensor fouling, and a lack of standardization across detection platforms add to the complexity of analysis. To improve recognition performance, several ways have been investigated, including surface functionalization, nanomaterial immobilization and substrate modification. These strategies seek to overcome limitations in sensitivity, repeatability, and environmental applicability. As a result, more advanced sensor platforms capable of detecting low concentrations in real time are urgently needed. This study highlights recent research on sensor and biosensor technologies used to detect PS-NPs, with a focus on the integration of nanomaterials and molecular recognition elements. Literature from ScienceDirect and IEEE Xplore indexed journals until June 2025 was reviewed. The findings indicate that hybrid sensor systems, particularly those employing plasmonic nanoparticles and functionalized nanostructures, are at the forefront of PS-NPs detection research. To find novel sensing methodologies, this review examines current technologies and compares their merits using recent case studies and performance analysis.

Keywords*:* *Sensor, Biosensor, Polystyrene, Nanoplastics*

1. INTRODUCTION

Since the first synthetic plastic was produced in the early 20th century, the worldwide population has become increasingly dependent on plastic. Plastics are highly beneficial in low production costs, stability, light weight, and adaptability, which has increased demand worldwide. With an annual rapid growth rate of 15% over the last 11 years [1], Malaysia alone is home to 1300 plastic manufacturing factories, making it one of the world's major plastic businesses [2]. Unfortunately, this prolific production activity has contributed to the rising amount of plastic waste. According to statistics, Malaysia was the eighth-largest plastic polluter in the world in 2021 and over 0.94 million tons of improperly managed plastic waste are produced annually in the country [2, 3].

Polystyrene (PS) is one of the commonly used thermoplastics, as it is versatile. It is also regarded for its low cost and broad application in packaging, insulation and disposable materials [4]. Unfortunately, extended exposure to styrene is associated with neurotoxicity that results in headaches, light-headedness, and possible cancerous effects. Hence, IARC has categorized polystyrene as a potentially carcinogenic substance (carcinogenicity class B2) [5].

Initially, PS plastic waste came from land disposal, wastewater treatment, tire wear, paint failure, textile washing, and marine casualties. These PS plastic waste are then accumulated, sank, and are consumed by creatures and re-distributed by currents in surface water [2, 6]. After going through significant environmental degradation, the plastics are broken into smaller pieces. This degradation results in the formation of polystyrene microplastics (PS-MPs) and [7–9] polystyrene nanoplastics (PS-NPs). These PS-MPs and PS-NPs can be categorized as primary or secondary sources. The industry produces primary microplastics, including PS-MPs, which are then released into the environment [10]. Particles are primarily sourced from cosmetics, medicines, paints, medical equipment, and electronics. In the cosmetic sector, they are usually components of face cleaning products, hand washing exfoliants, and peeling formulae [11]. NPs are also released during high-temperature engineering procedures. Other significant sources include plastic packaging manufacturing factories. Secondary sources are plastic particles that disintegrate into smaller pieces due to physical and chemical processes [12]. Improper plastic waste handling leads to the discharge of particles rinsed from synthetic fibers (**Figure 1**).

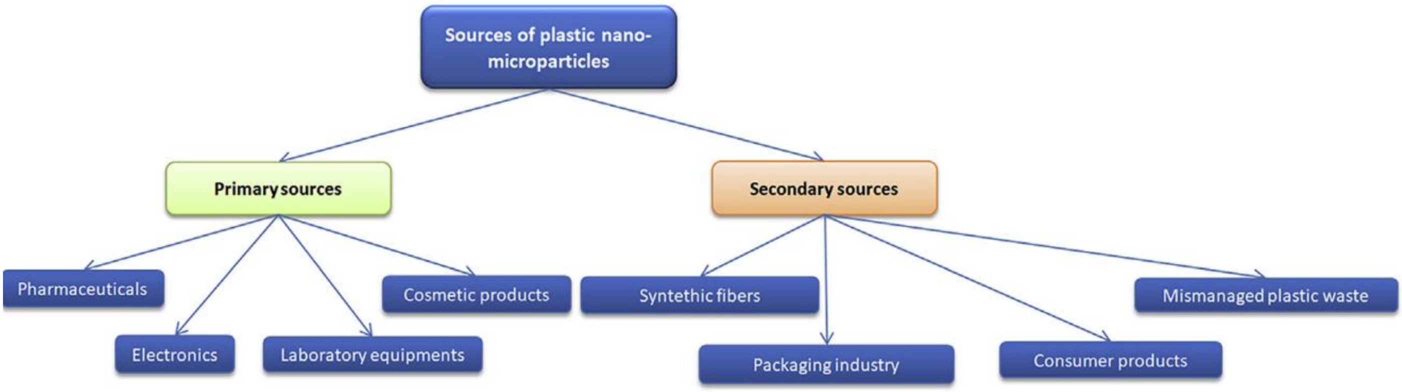

Figure 1. Primary and secondary sources of micro- and nanoplastic in the environment [5].

PS-NPs travel in a variety of ways, including air deposition, wastewater discharge, and disintegration from bigger plastics. PS-NPs' compact size allows them to reach even the most isolated habitats, from deep oceans to mountain peaks. PS-NPs frequently vary in form and surface structure, with diameters ranging from 1 to 100 nm [13]. Small particles have a higher surface area-to-volume ratio than bigger particles, which boosts their reactivity and potential for interaction with adjacent molecules. PS-NPs prefer to clump together in aquatic environments, which influences how they settle and their availability in marine habitats [14]. Additionally, PS-NPs can carry other pollutants, alter their environmental impact and potentially make them more toxic [15]. Studies have also verified that PS-NPs penetrate living organisms from the aquatic environment and accumulate in subsequent links of the food chain. It is found that PS-NPs enter embryos and accumulate in the yolk sac [16]. Another study by Mattsson *et al.* (2015) found accumulation of 24 and 27 nm PS-NPs in the food chain [17]. This accumulation is summarized in **Figure 2**.

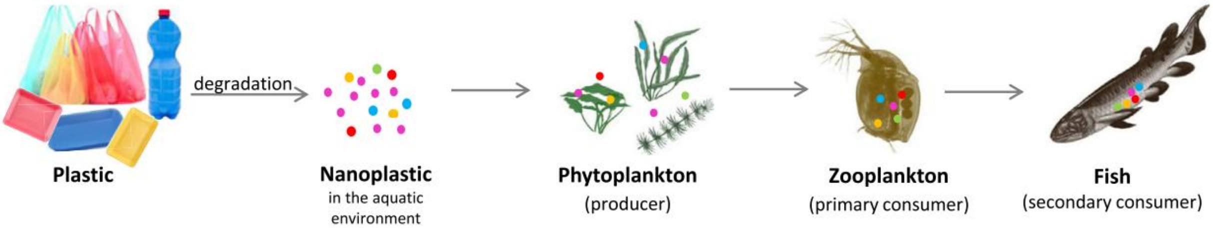

Figure 2. Accumulation of polystyrene nanoparticles in the food chain [5].

Due to their tiny size, widespread distribution and ability to accumulate, PS-NPs are extremely dangerous to living things in aquatic and marine environments. It has been demonstrated that exposure to 44 nm PS-NPs alters the bioenergetics of developing zebrafish, impacting their growth and metabolic functions. At the cellular level, PS-NPs also raise the zebrafish's cardiac apoptosis and reduce mitochondrial efficiency in ATP synthesis [18–24].

It has also been demonstrated that PS-NPs change gene expression and upset reproduction processes. A long-term exposure of water fleas *D. pulex* and *D. magna* to PS-NPs concentrations of 50 and 75 nm changes the gene expression implicated in stress defence and heat shock proteins, which impacts the antioxidant system and damages the organism [25–27]. After 3 weeks of PS-NPs exposure, the entire transcriptome of *D. pulex* was tested, revealing changes in the genes related to trehalose transport and metabolism, chitin metabolism, growth-related genetics, protective mechanisms, and sex differentiation. These changes resulted in ageing, delayed development and fertilization, and modifications to the population's sex and reproductive structure.

Despite their expanding environmental impact, detecting PS-NPs remains technically difficult. This is due to their nanoscale size, chemical complexity, and prone to congregate in aquatic environments [28]. Conventional techniques, such as electron microscopy and dynamic light scattering, provide excellent sensitivity but are constrained. Some barriers are included by the high cost, extensive sample preparation, and low output [28, 29]. As a result, sensors such as electrochemical, optical, and biosensing platforms have gained popularity. These sensors are known for their ability to provide real-time, portable, and low-cost alternatives.

Furthermore, advancements in π-π interaction-based recognition, functionalised nanostructures, and hybrid sensing systems provide exciting opportunities. As a result, this study presents a systematic literature review (SLR) utilising the PRISMA technique, with a focus on existing sensors for PS-NP detection in water samples. Section 2 describes the review methods. Section 3 summarizes and compares sensors for PS-NPs detection, including their performance metrics. Finally, in section 4, the conclusion is made.

2. REVIEW METHOD

The fundamental idea of a sensor in detecting PS-NPs is based on physicochemical properties that are altered when PS-NPs interact with the sensing element in general. The method enables PS-NPs detection and quantitation by converting its chemical signal of chemical compound concentration into a measurable change in the sensor's response [30, 31]. As polystyrene itself is a synthetic polymer, many studies are focused on the modification of the sensing surface or various sensing element approaches. This includes integrating the substrate with different types of receptors or bioreceptors such as nanostructure, protein, natural or synthetic polymer, aptamer, antibodies, enzymes and dyes [32–34].

Linear range, sensitivity, limit of detection (LoD) and relative standard deviation (RSD) are important indicators in evaluating a sensor's performance in detecting PS-NPs. Linear range refers to the concentration interval in which the signal response is linearly proportional to analyte concentration [35]. Sensitivity is the slope of that response [35, 36]. The LoD represents a minimal detectable concentration that can be differentiated from noise [36]. RSD measures repeatability and reliability over several measurements [37]. These factors collectively provide a full assessment of sensor performance in detecting PS-NPs [38, 39]. This research presents a thorough analysis of current methods for detecting PS-NPs in water samples. Advanced evaluation is one of the most important issues right now. Thus, a systematic flow strategy was adopted in this study. A systematic review is a way for deliberately discovering patterns, trends, and important assessments of the literature on study themes. The review technique included four steps to choose relevant papers for the study. This study utilized the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach [40]. This approach depicts the flow of information across the stages of a systematic review, as shown in **Figure 3**.

The first stage in producing a literature review is to locate relevant research items to the research question. The total number of papers searched was screened. Papers were evaluated for eligibility based on their abstracts. Further research was recommended to address the problems raised. This study employed the best practice method to perform a complete literature review. The publishing rules gave valuable information to help researchers evaluate the accuracy of the review. Furthermore, an inquiry into the systematic analysis of the many papers included in this review. The approaches were studied using the ScienceDirect and IEEE Xplore databases.

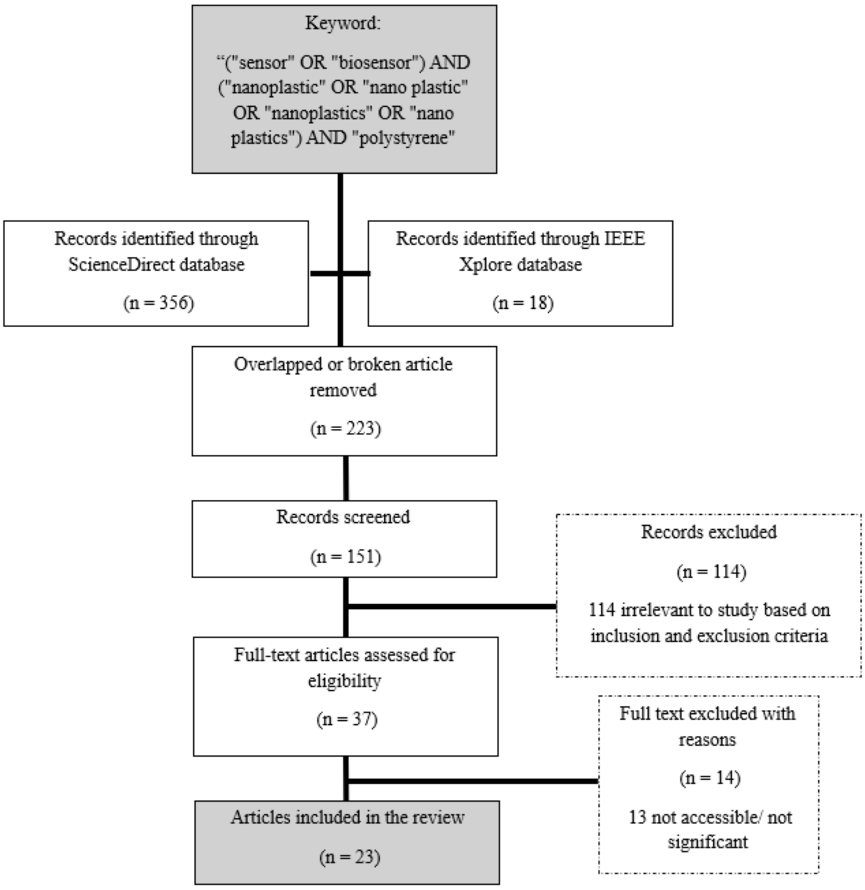

Figure 3. PRISMA flow diagram of the entire procedure in selecting reviewed articles.

2.1. Preliminary Identification

A selection of studies on different sensors in detecting PS-NPs was found in the literature. Keywords like “polystyrene”, "nanoplastic," "sensor," and "biosensor." To consider all relevant recent studies, the year was limited to 2021. ScienceDirect and IEEE Xplore databases were used to search the literature and articles. As shown in **Table 1**, the first search produced 356 articles from the ScienceDirect database and 18 articles from the IEEE Xplore database.

2.2. Screening

Screening identifies suitable research articles that correspond to predefined research questions. The first screening rejected 223 publications due to overlapped or visible broken articles, and the remaining 151 papers were examined using the study's exclusion and inclusion criteria as described in **Table 2**. The first need was to include research publications that provided practical guidance, such as reviews, encyclopedia, index, book series, chapters, and conference proceedings. These papers have been eliminated from recent investigations. English-language publications issued in 2025 are discussed and analysed. 114 articles were eliminated due to premature results and a lack of debate regarding the detection of PS-NPs in water samples. Some articles were partial or unavailable, with broken links and overlaps.

Table 1 Search strings from the ScienceDirect and IEEE Xplore databases

Database	Search Strings	Results
ScienceDirect	("sensor" OR "biosensor") AND ("nanoplastic" OR "nano plastic" OR "nanoplastics" OR "nano plastics") AND "polystyrene" Refined by: Document types: (Article) and Publication Year: 2025	356 Articles
IEEE Xplore	("All Metadata":"sensor" OR "All Metadata":"biosensor") AND ("All Metadata":"nanoplastic" OR "All Metadata":"nano plastic" OR "All Metadata":"nanoplastics" OR "All Metadata":"nano plastics") AND ("All Metadata":"polystyrene")	18

Table 2 Second-stage examination criteria

Criterion	Inclusion	Exclusion
Language	English	Non-English
Published Year	2025	<2025
Source Type	Journal (only research articles)	Conference proceeding
Document Type	Article	Letter, review, conference, and note
Research Area	Environmental and Engineering	Besides Environmental and Engineering

2.3. Eligibility

After meeting all inclusion and exclusion criteria, the final review sample was generated. The research objectives required articles that addressed studies and research in sensor development for detecting PS-NPs. 14 publications were excluded as their titles and abstracts did not align with the study's purpose based on empirical data. Finally, 23 papers and articles were made available for evaluation, as depicted in **Figure 3**.

3. PERFORMANCE METRICS OF CURRENT SENSORS FOR PS-NPS DETECTION

As the impacts of plastic pollution have become an alarming concern globally, many scientists and researchers are developing the best sensor to detect PS-NPs at the lowest concentration. Additionally, these studies are primarily focused on aquatic and marine habitats in environmental monitoring and analytical studies. However, precisely detecting and measuring PS-NPs remains difficult due to their nano-scale size, low ambient concentrations, and the complexity of sample matrices. In response, a comparative study of modern sensor and biosensor technologies was done to highlight the importance of material selection, surface functionalization, substrate immobilization and signal amplification methodologies. The performance metrics of these sensors were evaluated using linear range, sensitivity, limit of detection (LoD) and relative standard deviation (RSD). This review looked at how new sensing techniques, such as optical, electrochemical, and receptor-based platforms, can increase the efficiency and reliability of detecting PS-NPs in water samples. Researchers have devised a variety of approaches to overcome constraints in selectivity, interference, and detection in real-world samples. Notably, nanomaterial-enhanced sensors, such as those containing metal nanoparticles and protein, have received interest due to their high sensitivity and customizable surface chemistry. A rigorous literature search resulted in the selection of 23 peer-reviewed studies for extensive analysis and comparisons.

Many studies and experiments are being conducted to detect the lowest concentration possible of PS-NPs. Hence, **Table 3** summarizes and tabulates the recent sensors development and design, their linear range, sensitivity, LoD, RSD performance metrics and their advantages or novel approaches from the studies.

Table 3 Summary of recent sensors for PS-NPs detection

References	Sensors platform	Modification or material used	Linear Range (µg/mL)	Sensitivity	Limit of Detection (LoD) (g/mL)	Relative Standard Deviation (RSD) (%)	Advantages / novel approaches
[43]	Electrochemical	Silver (Ag) labelling	50 – 600	4.604 µA/(mg/mL)	13 µ	6.03 – 10.59	Simple. anti-interference, and low-cost.
[44]		Polyaniline coating magnetic biochar nanoparticles ($PA@MBC_{BM}$)	0.03 – 1	2.15 µA/(µg/L)	1.26 n	5.4 – 13.3	Outstanding elimination was assured in both cold and warm water with a pH range of 1 to 10.
[45]	Photoelectrochemical-electrochemical	CdS/CeO_2 heterojunction	0.5 – 800	7.92 µA/(µg/L)	0.38 n	0.4 – 2.97	The sensor displays selected modes and self-checking functions to ensure accurate detection
[46]	SERS	Aluminium and copper as nanoparticle-on-film (NPoF)	0 – 1000	0.92 a.u./(µg/mL)	1 µ	-	Plasmonic coupling amidst third-generation hotspots (TGHs) and second-generation hotspots (SGHs)
[47]		Nickel Oxide (NiO) nanosheet array decorated with Silver Nanoparticles (AgNPs)	100 – 2500	Drinking water: 1.77 a.u./(µg/mL) Milk: 0.396 a.u./(µg/mL) Liquor : 0.889 a.u./(µg/mL)	5 µ	4.70 – 8.54	Unique nanowell architecture alongside silver plasmonic enhancement
[48]		Honeycomb-like AgNPs@TiO2 array	100 – 2500	Tap water : 1.14 a.u./(µg/mL) Lake water : 1.34 a.u./(µg/mL)	100 µ	0.49 – 10.23	Novel honeycomb-like AgNPs

				Soil : 1.44 a.u./(µg/mL) Sea water: 0.51 a.u./(µg/mL)			
[49]		Silver nanoparticles (AgNPs) anchored on Nb_2CT_x (MXene)	0.1 – 100	131 a.u/(µg/mL)	100 n	2.88 – 8.30	Exhibits excellent stability of PS-NPs on different detection sites
[50]		Mesoporous spiked gold nanocrystals (AuNCs) are homogeneously deposited on a glass fiber filter membrane	0.1 – 200	-	100 n	6.91 – 7.62	Combination of membrane filtration technology and SERS
[51]		three-dimensional $Ti_3C_2T_x/TiO_2/W_{18}O_{49}$ semiconductor heterostructures	25 – 1000	Rainwater: 0.7804 a.u./(µg/mL) Soil: 0.8120 a.u./ µg/mL) Industrial wastewater: 0.6033 a.u./(µg/mL)	25 µ	12.58	Sensor's fingerprinting features enable the identification of other plastic types including polyethylene (PE) and polyethylene terephthalate (PET)
[52]		Polydomain aggregating silver nanoparticles (PASN) on a hydrophilic and a punched hydrophobic PVDF combined filter membrane	1 – 500	Tap water: 1360.03 a.u./ µg/mL) Lake water: 1677.53 a.u./ µg/mL)	1 µ	8.6	Using silver nanoparticles of different sizes to increase hotspot areas
[53]		Metal-free $Cu_2S@MoS_2$ nanoarray	50 – 2500	0.5 a.u./ µg/mL)	50 µ	10.3	Special approach of metal-free Cu2S@MoS2 nanoarray provides great sensitivity and repeatability
[54]		Gold sputtered glass slide cover	10 – 40	-	0.32 µ1	-	Experiment was carried out in the presence of interferences such as salts, sugars and amino acids to demonstrate great selectivity
[55]		Gold nanoparticles (AuNPs)	800 – 10,000	-	800 µ	-	Employing electric charge adsorption to

							enhance PS-NPs' SERS detection signal.
[56]		Nanowall SERS heterocomposite based on 3D D(C$_7$CO)-BTBT nanowalls and 2D few-layer MoS$_2$ flakes	0.4 – 50	-	0.45 µ	-	SERS property was enhanced by the synergistic effects of electromagnetic and charge transfer
[57]	Fluorescence	Organic dyes; Rhodmine6G, coumarin521, and fluorescein	-	-	20 n	-	Rapid analytical separation of dyes by capillary electrophoresis
[58]		Fluorescence Lifetime Analysis (FLA)	10 – 1000	-	10 µ	-	Endogenous fluorescence has been used to identify PS-NPs materials.
[59]	Optical	metal-organic framework (MOF) ZIF-8 functionalized S-tapered fiber (STF)	100 – 800	114.1353 nm/% (w/v)	1.8 µ	-	Strong electrostatic adsorption effect and π-π stacking with PS-NPs
[60]		Microfiber	1×10^{-8} – 10	1.229 nm/log10(mg/mL)	1.23 n	2.443	Operando on-line quantification of PS-NPs
[61]	Optofluidic	Laser-backscattered fiber-embedded optofluidic chip (LFOC)	0 – 100	0.00273 /(µg/mL)	0.23 µ	0.50 – 6.36	LFOC unique features include plug and play, reagent-free, field-deployment, low-cost
[62]	Colorimetric	single-atom nanozyme of zeolitic imidazolate framework (ZIF-FeSAN) was prepared using hemoglobin as template and Fe-source	0 – 20	8.1 a.u./(mg/mL))	212 n	0.61 – 4.48	ZIF-FeSAN possess good adsorption characteristics for PS-NPs via electrostatic and π-π interactions
[63]		Mercaptoundecanoic acid (MUA)-functionalized gold nanoparticles (AuNPs)	0 – 1300	0.616/(mg/mL)	26 n	10	Able to quickly visualize the separation of PS-NPs less than 100 nm
[64]	Triboelectric nanogenerators (TENG)	BaTiO$_3$-PDMS nanocomposite films	0 – 0.08	9.44 V/µwt%	0.823 n	0.084 – 1.13	Combined with Deep Learning algorithm to identify PS-NPs
[65]	Spectroscopy	Mie scattering	0.1 – 10	139.5 a.u./(g/mL)	4.2 n	3.8 – 5.4	This method instantly detects a sample within

							20 seconds, removing the requirement for pretreatment.

3.1. Linear Range and Sensitivity

Linear range is the concentration window within which a sensor maintains proportionality between signal and analyte concentrations. As for sensitivity, it quantifies signal change per unit analyte. If a sensor responds linearly, its sensitivity remains constant across its range and equals the slope of the straight-line plot [35]. Although these parameters are closely related, they are not directly proportional. In Table 3, SERS sensors possessed extremely high sensitivity but have narrower linear ranges due to signal saturation. However, some of the SERS sensors contain wide linear ranges but have lower sensitivity to maintain proportionality across diverse concentrations. AgNPs@TiO_2 array SERS sensor by Li *et al.* (2024) has a small working window skewed towards high concentrations, at 100 to 2500 μg/mL) [48]. This sensor is suitable for higher concentration samples that require substantial plasmonic amplification. Mesoporous Au nanocrystals SERS sensor gives a greater dynamic range at 10 to 1000 μg/mL [50]. Polydomain aggregating silver nanoparticles (PASN) SERS sensor has the steepest calibration slope, up to 1677.53 a.u./$\mu g \cdot mL^{-1}$. This indicates substantial signal enhancement and is ideal for exact quantification and detection of PS-NPs at moderate-to-high concentrations [49, 52]. TiO_2 semiconductor heterostructures SERS sensor, however, are less susceptible to changes in concentration, indicated by their slightly different sensitivity values when tested on various water samples [51].

The microfibre optical sensor has a wide linear range of 1×10^{-8} μg/mL to 10 μg/mL. Hence, making it ideal for monitoring PS-NPs at ultra-trace and ambient levels [60, 66, 67]. The LFOC optofluidic sensor has poorer sensitivity at 0.00273 /μg·mL. This indicates a slower reaction to incremental concentration changes [67]. However, their lower sensitivity is frequently offset by their mobility, real-time monitoring capability, and reagent-free operation. Both colorimetric sensors fall somewhere in the centre, offering modest sensitivity while remaining user-friendly and low-cost. MUA-functionalized AuNPs colorimetric sensor by Zhou *et al.* (2023) offers a wider linear range interval [63]. However single-atom nanozyme of ZIF-FeSAN colorimetric sensor by Hu *et al.* (2024) offers better sensitivity [62]. Hence, both sensors are fit for quick screening but less effective for extremely precise detection in real water samples. This variance in linear range demonstrates a compromise between sensitivity augmentation techniques and capacity to retain linearity over a wide concentration range [66, 67].

3.2. Limit of Detection (LoD)

Based on Table 3, Surface-enhanced Raman spectroscopy (SERS) sensors are the most developed and explored approach in detecting PS-NPs. SERS are integrated or modified with different nanomaterials to enhance their sensitivity and selectivity. AgNPs anchored on Nb_2CT_x (MXene) SERS sensor [49] and Mesoporous spiked AuNCs SERS sensor [50] both have the lowest LoD compared to other SERS approaches at 100 ng/mL. As polystyrene uniquely possesses aromatic structure of benzene rings, this structure creates distinct Raman peaks, such as those at ~1000 cm^{-1} and ~1600 cm^{-1} [46, 55]. Its distinctive vibrational modes make it easily detectable in SERS spectra, even at low concentrations.

Other sensor platforms such as polyaniline coating magnetic biochar nanoparticles (PA@MBC_{BM}) electrochemical sensor, organic dyes fluorescence sensor, microfiber optical sensor and MUA functionalized AuNPs colorimetric sensor have the lowest LoD at 1.26 ng/mL [44], 20 ng/mL [57], 1.23 ng/mL [60] and 26 ng/mL [63], respectively. However, the lowest LoD is captured by CdS/ CeO_2 heterojunction photoelectrochemical-electrochemical sensor by Xiao *et al.* (2024) at 0.38 ng/mL [45]. CdS is a semiconductor that absorbs light well yet has a high electron-hole recombination rate. Combining it with CeO_2, which has stable redox characteristics (Ce^{3+}/Ce^{4+}), results in a heterojunction that promotes charge separation and photoactivity [68, 69]. CdS/CeO_2 is a highly appealing substance for dual-mode sensors, particularly in addressing electron transfer difficulties induced by protein interactions with PS-NPs in aquatic settings.

Some reagent package inserts may state that an assay has a dynamic range that extends from zero concentration to an upper limit. However, most assays cannot properly quantify analyte concentrations at zero. A minimum concentration of analyte is required to provide an analytical signal that can be consistently separated from background noise. This reflects the signal observed in the absence of the analyte [70]. Hence, several approaches are used in some of the studies reviewed in this paper to estimate the LoD. This includes visual definitions, signal-to-noise ratio estimation (three or two times the noise level), calculation from the standard deviation of the blank and calculation from the calibration line at low concentrations [36, 71].

Polyaniline coating magnetic biochar nanoparticles (PA@MBC_{BM}) electrochemical sensor by Wang *et al.* (2025) calculated LoD using the $3\sigma/S$ formula, where σ and S represent blank standard deviation and slope of the linear curve, respectively. With LoD at 1.26 ng/mL, it is lower than nanoplastics electrochemically labelled with Ag, at 13 μg/mL. Similarly, this Ag labelling electrochemical sensor developed by Zhao *et al.* (2024) also applied the 3N/S formula to calculate LoD. The N represents the standard deviation of the blank signal and S represents the slope of the calibration curve [43, 72]. This same formula is also applied in calculating LoD for LFOC optofluidic sensor [61] and single-atom nanozyme ZIF-FeSAN colorimetric sensor [62].

CdS/CeO_2 heterojunction photoelectrochemical-electrochemical sensor by Xiao *et al.* (2024) calculated LoD by using $3\ s_b/m$ formula, where s_b is the standard deviation of the response and m is the slope of the calibration curve [45, 73]. Gold sputtered glass slide cover SERS sensor by Chaisrikhwun *et al.* (2023) calculated LoD based on the standard deviation of the response (σ) and the slope of the calibration curve (S), using the equation, $LOD = 3.3\sigma/S$ [54]. $BaTiO_3$-PDMS nanocomposite films TENG sensor calculated LoD by using the formula $LoD = K\sigma/k$. Where K is the confidence factor, generally taken as 3, σ is the standard deviation of the blank sample, calculated to be 0.2593, and k is the slope of the standard curve over the low concentration range [64].

3.3. Relative Standard Deviation (RSD)

RSD is an important performance parameter for sensors since it represents the accuracy of repeated measurements. A low RSD (e.g., < 5%) value implies that the sensor itself can deliver consistent findings under the same settings, hence proving repeatability [74]. Maintaining minimal RSD values is necessary to ensure reproducibility across multiple runs in laboratories and real sample settings [49]. When comparing across the sensor platforms, both the microfiber colorimetric sensor and the LFOC optofluidic sensor have continuously low RSD values. Both sensors have RSD values of less than 5%, which makes them the most reproducible platforms [60, 61]. For the SERS sensor, it varies in sensitivity and material design. The honeycomb-like AgNPs@TiO_2 array SERS sensor has the lowest minimum RSD at 0.49%, indicating exceptional precision under optimal conditions. However, its wider range of up to 10.23% indicates more variability among measurements. AgNPs anchored on Nb_2CT_x (MXene) SERS sensor have a narrower and more stable RSD range (2.88–8.30%), indicating improved consistency and reliability. Although the honeycomb-like AgNPs@TiO_2 array SERS sensor can achieve higher repeatability in the best scenario, the MXene-based SERS sensor has lower total RSD variability, making it more trustworthy throughout repeated tests.

Based on Table 3, the $BaTiO_3$-PDMS nanocomposite films TENG sensor has the lowest RSD (0.084 to 1.13%) as compared to other sensors. This unusually low RSD indicates that TENG sensors are less susceptible to signal fluctuations and external disturbances. The sensor's high repeatability also boosts credibility in controlled laboratory tests and real samples, where sample heterogeneity and operational unpredictability can challenge sensor performance.

3.4. Nanomaterials

Metal nanoparticles are one of the most utilized nanomaterials to increase the device's performance in terms of analyte recognition. Metal nanoparticles propose unique features such as optical, electrical and excellent catalytic properties [33, 75–77]. SERS performance was connected to the number of PS-NPs surrounded by the gold nanoparticles (AuNPs), and the strength of the superposition electric field would have a gradual linear relationship with the number of charged surrounding PS-NPs, as proven by Lan *et al.* (2024) [55].

Some nanomaterials, particularly noble metals such as AgNPs, raise concerns about their environmental safety. While AgNPs contribute significantly to sensitivity enhancement through localized surface plasmon resonance, as demonstrated in NiO/AgNPs nanowall SERS sensor by Li *et al.*, 2025 [47] and AgNPs anchored on Nb_2CT_x MXene SERS sensor by Chang *et al.* (2024) [50], respectively. They are also known to be toxic to aquatic organisms when released in excess. The toxicity mechanism of AgNPs is mostly owing to their ability to create a huge amount of Reactive Oxygen Species (ROS), which can damage the cell membrane and cause cell death. Specifically, AgNPs are quickly oxidized by O_2 and other molecules, resulting in Ag^+. Excessive and continuous ROS will cause oxidative stress [78, 79]. Leaching of free Ag^+ ions or unbound nanoparticles into the environment might lead to secondary pollution, worsening the conditions the sensors are monitoring. Because of the dual nature of AgNPs, more research is needed into their long-term environmental impact, biocompatibility, and potential leaching behavior during sensor deployment in the field.

Interestingly, some sensor materials can not only detect PS-NPs but also reduce their toxicity by their anti-microbial properties. Wang *et al.* (2025) produced a polyaniline-coated magnetic biochar ($PA@MBC_{BM}$) electrochemical sensor, which was demonstrated to be effective throughout a wide pH and temperature range and contributed to the elimination of PS-NPs during detection [44]. This dual functionality provides a viable avenue for developing a multifunctional sensing device that integrates detection and remediation. Similarly, the ZIF-FeSAN nanozyme colorimetric sensor revealed high adsorption of PS-NPs via electrostatic and π-π interactions by Hu *et al.* (2024), indicating a potential "trapping" effect that may limit the bioavailability of nanoplastics in water [59]. These findings highlight a new trend in sensor research: developing materials that not only detect contaminants with great precision but also contribute to their neutralization or sequestration.

3.5. Sensors interaction with PS-NPs

Aromatic π-π interactions are a crucial chemical recognition technique in developing sensors for PS-NPs recognition due to the strong affinity between the aromatic rings of polystyrene and the π-conjugated sensor materials [80]. In an electrochemical sensor with polyaniline coating, magnetic biochar nanoparticles ($PA@MBC_{BM}$)

electrochemical sensor by Wang *et al.* (2025), PS-NPs adsorption resulted in enhanced binding energy and aromatic carbon content (C=C, sp^2), indicating that π-π interaction was responsible for their attachment [44].

Xiong *et al*. (2024) discovered that ZIF-8 possesses a high electrostatic adsorption interaction with PS-NPs. The benzene-like ring structure of ZIF-8 and PSNPs makes π-π stacking more effective for adsorption. ZIF-8 serves as a bridge, communicating changes in PS-NP concentration and evanescent waves across the S-tapered fibre (STF) surface [59]. Hence, a high-sensitivity optical-fiber sensor is achieved. Similar findings are also demonstrated by Li *et al*. (2024), the fabricated microfiber optical sensor can continuously detect PS-NPs via strong benzene ring π-π stacking interaction between the L-Phenylalanine (L-PHA) and the PS-NPs particles (**Figure 4**) [60]. A single-atom nanozyme of zeolitic imidazolate framework (ZIF-FeSAN) colorimetric sensor developed by Hu *et al*. (2024) revealed that ZIF-FeSAN has significant adsorption for PS-NPs with the active centre of Fe atom shielding, and peroxidase-like activity can be greatly lowered after adsorption of PS-NPs. This is due to electrostatic and π-π interaction [62].

The Ag labelling electrochemical sensor developed by Zhao *et al.* (2024) utilized the electrochemical reaction of Ag to quantify PS-NPs. Electrostatic interaction connected Ag^+ to the PS surface. The Ag^+ surface was then reduced to Ag nanoparticles (AgNPs) by $NaBH_4$. This allows the AgNPs to interact with PS-NPs, resulting in an Ag-PS complex. The free AgNPs were isolated from the Ag-PS using standing flotation. Hence, the concentration of PS-NPs was calculated by measuring the current response of Ag [43].

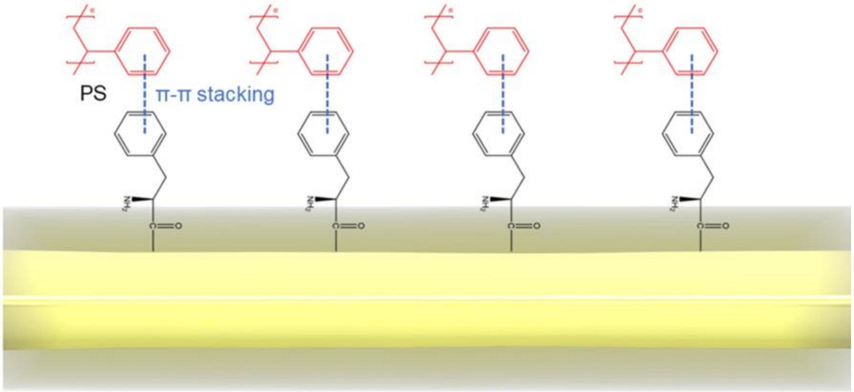

Figure 4. Schematic illustrations of the binding of L-PHA probe molecules with PS-NPs on the surface of optical microfiber [60].

3.6. Other Performance Metrics

High coefficients of determination (R^2) and high recovery rate sensor peaks demonstrate consistent hotspot distribution and signal intensity throughout several tests. High R^2 is necessary in environmental monitoring to guarantee field measurement confidence, particularly when detecting extremely low PS-NPs concentrations, where even small errors might cause contamination levels to be misinterpreted. Yang *et al.* (2025) portable SERS chessboard substrate displays excellent coefficients of determination with 0.9916 or 99.16% of R^2 [52]. Furthermore, the use of a single-atom nanozyme-enabled strategy for rapid, visual, and real-time detection, as demonstrated by Hu *et al*. (2024). The sensor offers high satisfactory recoveries, ranging from 91.47% to 108.12% and good selectivity, which makes it useful for different water samples [62].

Spectroscopy sensors with implying principles of Mie scattering have good anti-interference ability. The approach was confirmed by the sensor's satisfactory recoveries, ranging from 82.4% to 110.3% of the self-ground PS-NPs. The approach directly measured the total amounts of NPs in the five commercial bottled water brands [65]. Satisfactory recoveries indicate the sensor provides accurate and reliable measurements of the target analyte with minimal error. These findings verified that optimizing the sensor design and incorporating advanced nanomaterials can result in excellent repeatability, which is crucial for environmental applications requiring reliable data over long-term deployments.

CONCLUSION

In conclusion, recent advances in sensor technologies for detecting PS-NPs have resulted in significant increases in sensitivity, selectivity, and repeatability, with several platforms now capable of detecting PS-NPs at environmentally relevant levels. Many sensors utilized nanomaterials to enhance the ability to identify the target analyte. Nanomaterials such as AgNPs in sophisticated heterostructures have been crucial in improving signal output and detecting precision. However, concerns surround the environmental toxicity of some nanomaterials, particularly AgNPs. This danger of nanoparticle leaking remains a major issue that deserve additional exploration. However, many studies have discovered that the AgNPs synthesization methods produced by the green method are safer and have higher biocompatibility when exposed to marine and aquatic habitats. Many studies also have discovered that some nanomaterials offer anti-microbial properties in reducing AgNPs toxicity. This can benefit in a variety of ways, including lowering PS-NP accumulation in marine life and organisms, limiting the formation of damaging biofilms, and directly counteracting PS-NP toxicity on cells and tissues. Additionally, π–π interactions play a vital role in PS-NPs sensor design, as demonstrated across various studies of π-conjugated sensor materials, enabling strong adsorption and high sensitivity through π−π stacking with the benzene rings of PS-NPs. Several sensor platforms also promise dual functionality, allowing for both detection and partial remediation of PS-NPs in water systems. Moving forward, next-generation sensors should focus on increasing sensitivity to increasingly tiny plastic contaminants, such as pico-sized plastics, while also combining biocompatible and environmentally acceptable materials. Future designs should also focus on sensor miniaturization, real-time in situ detection capability, and interaction with the Internet of Things (IoT) for environmental monitoring and risk assessment.

ACKNOWLEDGMENTS

The author would like to acknowledge the support from the Fundamental Research Grant Scheme (FRGS) under a grant number of FRGS/1/2024/TK07/UNIMAP/02/2 from the Ministry of Higher Education Malaysia.

REFERENCES

[1] Y. C. Moh and L. Abd Manaf, “Overview of household solid waste recycling policy status and challenges in Malaysia,” *Resour Conserv Recycl*, vol. 82, pp. 50–61, Jan. 2014, doi: 10.1016/J.RESCONREC.2013.11.004.

[2] H. L. Chen, T. K. Nath, S. Chong, V. Foo, C. Gibbins, and A. M. Lechner, “The plastic waste problem in Malaysia: management, recycling and disposal of local and global plastic waste,” Apr. 01, 2021, *Springer Nature*. doi: 10.1007/s42452-021-04234-y.

[3] N. Santodomingo, C. Perry, Z. Waheed, M. A. bin Syed Hussein, A. Rosedy, and K. G. Johnson, “Marine litter pollution on coral reefs of Darvel Bay (East Sabah, Malaysia),” *Mar Pollut Bull*, vol. 173, no. Pt A, Dec. 2021, doi: 10.1016/J.MARPOLBUL.2021.112998.

[4] K. J. Groh, H. P. H. Arp, M. MacLeod, and Z. Wang, “Assessing and managing environmental hazards of polymers: historical development, science advances and policy options,” *Environ Sci Process Impacts*, vol. 25, no. 1, pp. 10–25, Dec. 2022, doi: 10.1039/D2EM00386D.

[5] K. Kik, B. Bukowska, and P. Sicińska, “Polystyrene nanoparticles: Sources, occurrence in the environment, distribution in tissues, accumulation and toxicity to various organisms,” *Environ Pollut*, vol. 262, Jul. 2020, doi: 10.1016/J.ENVPOL.2020.114297.

[6] J. R. Jambeck *et al.*, “Plastic waste inputs from land into the ocean,” *Science (1979)*, vol. 347, no. 6223, pp. 768–771, Feb. 2015, doi: 10.1126/SCIENCE.1260352/SUPPL_FILE/JAMBECK.SM.PDF.

[7] S. E. Nelms *et al.*, “Microplastics in marine mammals stranded around the British coast: ubiquitous but transitory?,” *Sci Rep*, vol. 9, no. 1, Dec. 2019, doi: 10.1038/S41598-018-37428-3.

[8] A. Lusher, “Microplastics in the marine environment: Distribution, interactions and effects,” *Marine Anthropogenic Litter*, pp. 245–307, Jan. 2015, doi: 10.1007/978-3-319-16510-3_10/FIGURES/1.

[9] J. C. Anderson, B. J. Park, and V. P. Palace, “Microplastics in aquatic environments: Implications for Canadian ecosystems,” *Environmental Pollution*, vol. 218, pp. 269–280, Nov. 2016, doi: 10.1016/J.ENVPOL.2016.06.074.

[10] W. J. Shim, S. H. Hong, and S. Eo, “Marine Microplastics: Abundance, Distribution, and Composition,” *Microplastic Contamination in Aquatic Environments: An Emerging Matter of Environmental Urgency*, pp. 1–26, Jan. 2018, doi: 10.1016/B978-0-12-813747-5.00001-1.

[11] I. Efimova, M. Bagaeva, A. Bagaev, A. Kileso, and I. P. Chubarenko, “Secondary microplastics generation in the sea swash zone with coarse bottom sediments: Laboratory experiments,” *Front Mar Sci*, vol. 5, no. SEP, p. 402880, Sep. 2018, doi: 10.3389/FMARS.2018.00313/BIBTEX.

[12] F. De Falco *et al.*, “Evaluation of microplastic release caused by textile washing processes of synthetic fabrics,” *Environmental Pollution*, vol. 236, pp. 916–925, May 2018, doi: 10.1016/J.ENVPOL.2017.10.057.

[13] M. B. Paul *et al.*, “Micro- and nanoplastics – current state of knowledge with the focus on oral uptake and toxicity,” *Nanoscale Adv*, vol. 2, no. 10, pp. 4350–4367, Oct. 2020, doi: 10.1039/D0NA00539H.

[14] Y. Guo *et al.*, “Aggregation behavior of polystyrene nanoplastics: Role of surface functional groups and protein and electrolyte variation,” *Chemosphere*, vol. 350, p. 140998, Feb. 2024, doi: 10.1016/J.CHEMOSPHERE.2023.140998.

[15] S. Guo *et al.*, “Environmental relevant concentrations of polystyrene nanoplastics and lead co-exposure triggered cellular cytotoxicity responses and underlying mechanisms in Eisenia fetida,” *Science of The Total Environment*, vol. 905, p. 167264, Dec. 2023, doi: 10.1016/J.SCITOTENV.2023.167264.

[16] Y. Chae, D. Kim, S. W. Kim, and Y. J. An, “Trophic transfer and individual impact of nano-sized polystyrene in a four-species freshwater food chain,” *Sci Rep*, vol. 8, no. 1, pp. 1–11, Dec. 2018, doi: 10.1038/S41598-017-18849-Y;TECHMETA=14,19,28,34;SUBJMETA=169,172,4081,704,895;KWRD=ENVIRONMENTAL+IMPACT,ENVIRONMENTAL+MONITORING.

[17] K. Mattsson, L. A. Hansson, and T. Cedervall, “Nano-plastics in the aquatic environment,” *Environ Sci Process Impacts*, vol. 17, no. 10, pp. 1712–1721, Oct. 2015, doi: 10.1039/C5EM00227C.

[18] R. Trevisan, R. Trimpey-Warfhatig, K. Gaston, L. Butron, S. Gaballah, and R. T. Di Giulio, “Polystyrene Nanoplastics Impact the Bioenergetics of Developing Zebrafish and Limit Molecular and Physiological Adaptive Responses to Acute Temperature Stress,” 2024, doi: 10.2139/SSRN.4986532.

[19] Y. Gu *et al.*, "Bioaccumulation of functionalized polystyrene nanoplastics in sea cucumber Apostichopus japonicus (Selenka, 1867) and their toxic effects on oxidative stress, energy metabolism and mitochondrial pathway," *Environmental Pollution*, vol. 319, p. 121015, Feb. 2023, doi: 10.1016/J.ENVPOL.2023.121015.

[20] T. Balbi *et al.*, "Impact of cationic polystyrene nanoparticles (PS-NH2) on early embryo development of Mytilus galloprovincialis: Effects on shell formation," *Chemosphere*, vol. 186, pp. 1–9, Nov. 2017, doi: 10.1016/J.CHEMOSPHERE.2017.07.120.

[21] M. Capolupo, S. Franzellitti, P. Valbonesi, C. S. Lanzas, and E. Fabbri, "Uptake and transcriptional effects of polystyrene microplastics in larval stages of the Mediterranean mussel Mytilus galloprovincialis," *Environmental Pollution*, vol. 241, pp. 1038–1047, Oct. 2018, doi: 10.1016/J.ENVPOL.2018.06.035.

[22] C. Della Torre *et al.*, "Accumulation and embryotoxicity of polystyrene nanoparticles at early stage of development of sea urchin embryos Paracentrotus lividus," *Environ Sci Technol*, vol. 48, no. 20, pp. 12302–12311, Oct. 2014, doi: 10.1021/ES502569W.

[23] A. Pinsino *et al.*, "Amino-modified polystyrene nanoparticles affect signalling pathways of the sea urchin (Paracentrotus lividus) embryos," *Nanotoxicology*, vol. 11, no. 2, pp. 201–209, Feb. 2017, doi: 10.1080/17435390.2017.1279360.

[24] M. C. Eliso *et al.*, "Application of transcriptome profiling to inquire into the mechanism of nanoplastics toxicity during Ciona robusta embryogenesis," *Environmental Pollution*, vol. 318, p. 120892, Feb. 2023, doi: 10.1016/J.ENVPOL.2022.120892.

[25] B. De Felice, M. Sugni, L. Casati, and M. Parolini, "Molecular, biochemical and behavioral responses of Daphnia magna under long-term exposure to polystyrene nanoplastics," *Environ Int*, vol. 164, p. 107264, Jun. 2022, doi: 10.1016/J.ENVINT.2022.107264.

[26] Z. Liu *et al.*, "Polystyrene nanoplastic exposure induces immobilization, reproduction, and stress defense in the freshwater cladoceran Daphnia pulex," *Chemosphere*, vol. 215, pp. 74–81, Jan. 2019, doi: 10.1016/J.CHEMOSPHERE.2018.09.176.

[27] W. Zhang, Z. Liu, S. Tang, D. Li, Q. Jiang, and T. Zhang, "Transcriptional response provides insights into the effect of chronic polystyrene nanoplastic exposure on Daphnia pulex," *Chemosphere*, vol. 238, p. 124563, Jan. 2020, doi: 10.1016/J.CHEMOSPHERE.2019.124563.

[28] C. Fang, Y. Luo, and R. Naidu, "Microplastics and nanoplastics analysis: Options, imaging, advancements and challenges," *TrAC Trends in Analytical Chemistry*, vol. 166, p. 117158, Sep. 2023, doi: 10.1016/J.TRAC.2023.117158.

[29] N. P. Ivleva, "Chemical Analysis of Microplastics and Nanoplastics: Challenges, Advanced Methods, and Perspectives," *Chem Rev*, vol. 121, no. 19, pp. 11886–11936, Oct. 2021, doi: 10.1021/ACS.CHEMREV.1C00178/ASSET/IMAGES/LARGE/CR1C00178_0015.JPEG.

[30] H. A. Saputra, "Electrochemical sensors: basic principles, engineering, and state of the art," *Monatsh Chem*, vol. 154, no. 10, pp. 1083–1100, Oct. 2023, doi: 10.1007/S00706-023-03113-Z/METRICS.

[31] H. A. Saputra, "Electrochemical sensors: basic principles, engineering, and state of the art," *Monatsh Chem*, vol. 154, no. 10, pp. 1083–1100, Oct. 2023, doi: 10.1007/S00706-023-03113-Z/METRICS.

[32] W. J. Shim, S. H. Hong, and S. E. Eo, "Identification methods in microplastic analysis: a review," *Analytical Methods*, vol. 9, no. 9, pp. 1384–1391, Mar. 2017, doi: 10.1039/C6AY02558G.

[33] Y. Tang, T. J. Hardy, and J. Y. Yoon, "Receptor-based detection of microplastics and nanoplastics: Current and future," Aug. 15, 2023, *Elsevier Ltd*. doi: 10.1016/j.bios.2023.115361.

[34] Y. Picó and D. Barceló, "Analysis of microplastics and nanoplastics: How green are the methodologies used?," *Curr Opin Green Sustain Chem*, vol. 31, p. 100503, Oct. 2021, doi: 10.1016/J.COGSC.2021.100503.

[35] M. J. McGrath and C. N. Scanaill, "Sensing and Sensor Fundamentals," *Sensor Technologies*, pp. 15–50, 2013, doi: 10.1007/978-1-4302-6014-1_2.

[36] A. Shrivastava and V. Gupta, "Methods for the determination of limit of detection and limit of quantitation of the analytical methods," *Chronicles of Young Scientists*, vol. 2, no. 1, p. 21, 2011, doi: 10.4103/2229-5186.79345.

[37] J. Shieh, J. E. Huber, N. A. Fleck, and M. F. Ashby, "The selection of sensors," *Prog Mater Sci*, vol. 46, no. 3–4, pp. 461–504, Jan. 2001, doi: 10.1016/S0079-6425(00)00011-6.

[38] T. Kögel, Ø. Bjorøy, B. Toto, A. M. Bienfait, and M. Sanden, "Micro- and nanoplastic toxicity on aquatic life: Determining factors," *Sci Total Environ*, vol. 709, Mar. 2020, doi: 10.1016/J.SCITOTENV.2019.136050.

[39] K. Zhao *et al.*, "Separation and characterization of microplastic and nanoplastic particles in marine environment," *Environmental Pollution*, vol. 297, p. 118773, Mar. 2022, doi: 10.1016/J.ENVPOL.2021.118773.

[40] S. H. Cho and I. S. Shin, "A reporting quality assessment of systematic reviews and meta-analyses in sports physical therapy: A review of reviews," *Healthcare (Switzerland)*, vol. 9, no. 10, p. 1368, Oct. 2021, doi: 10.3390/HEALTHCARE9101368/S1.

[41] G. Wu, H. Zheng, Y. Xing, C. Wang, X. Yuan, and X. Zhu, "A sensitive electrochemical sensor for environmental toxicity monitoring based on tungsten disulfide nanosheets/hydroxylated carbon nanotubes nanocomposite," *Chemosphere*, vol. 286, p. 131602, Jan. 2022, doi: 10.1016/J.CHEMOSPHERE.2021.131602.

[42] H. Sun, H. Zheng, Z. Zhang, Y. Liu, J. Qu, and X. Zhu, "Cytotoxicity assessment of nanoplastics and associated additives using an electrochemical sensor based on carbon nanohorn/gold nanoparticles," *J Environ Chem Eng*, vol. 11, no. 6, p. 111452, Dec. 2023, doi: 10.1016/J.JECE.2023.111452.

[43] Z. Zhao, X. Zhao, J. Shan, and X. Wang, "Concentration analysis of metal-labeled nanoplastics in different water samples using electrochemistry," *Science of The Total Environment*, vol. 907, p. 168013, Jan. 2024, doi: 10.1016/J.SCITOTENV.2023.168013.

[44] P. Wang *et al.*, "Robust polyaniline coating magnetic biochar nanoparticles for fast and wide pH and temperature range removal of nanoplastics and achieving label free detection," *Water Res*, vol. 277, p. 123313, Jun. 2025, doi: 10.1016/J.WATRES.2025.123313.

[45] Z. Xiao, S. Hong, Y. Chen, Z. Zhang, and Y. Zhang, "Smart and accurate detection of nanoplastics in aquatic environments by photoelectrochemical-electrochemical dual-mode portable sensor," *Sens Actuators B Chem*, vol. 420, p. 136483, Dec. 2024, doi: 10.1016/J.SNB.2024.136483.

[46] U. Pant, J. Tate, X. Liu, N. Birse, C. Elliott, and C. Cao, "From automated Raman to cost-effective nanoparticle-on-film (NPoF) SERS spectroscopy: A combined approach for assessing micro- and nanoplastics released into the oral cavity from chewing gum," *J Hazard Mater*, vol. 486, Mar. 2025, doi: 10.1016/J.JHAZMAT.2024.136978,.

[47] Z. Li *et al.*, "NiO/AgNPs nanowell enhanced SERS sensor for efficient detection of micro/nanoplastics in beverages," *Talanta*, vol. 281, p. 126877, Jan. 2025, doi: 10.1016/J.TALANTA.2024.126877.

[48] Z. Li *et al.*, "Honeycomb-like AgNPs@TiO2 array SERS sensor for the quantification of micro/nanoplastics in the environmental water samples," *Talanta*, vol. 266, p. 125070, Jan. 2024, doi: 10.1016/J.TALANTA.2023.125070.

[49] L. Chang *et al.*, "Quantitative detecting low concentration polystyrene nanoplastics in aquatic environments via an Ag/Nb2CTx (MXene) SERS substrate," *Talanta*, vol. 273, p. 125859, Jun. 2024, doi: 10.1016/J.TALANTA.2024.125859.

[50] Y. Qin, J. Qiu, N. Tang, Y. Wu, W. Yao, and Y. He, "Controllable preparation of mesoporous spike gold nanocrystals for surface-enhanced Raman spectroscopy detection of micro/nanoplastics in water," *Environ Res*, vol. 228, p. 115926, Jul. 2023, doi: 10.1016/J.ENVRES.2023.115926.

[51] K. Han *et al.*, "High-sensitivity SERS sensor leveraging three-dimensional Ti3C2Tx/TiO2/W18O49 semiconductor heterostructures for reliable detection of trace micro/nanoplastics in environmental matrices," *Talanta*, vol. 286, p. 127474, May 2025, doi: 10.1016/J.TALANTA.2024.127474.

[52] Z. Yang *et al.*, "One-step detection of nanoplastics in aquatic environments using a portable SERS chessboard substrate," *Talanta*, vol. 282, p. 127076, Jan. 2025, doi: 10.1016/J.TALANTA.2024.127076.

[53] A. Zhang *et al.*, "Nano-arrayed Cu2S@MoS2 heterojunction SERS sensor for highly sensitive and visual detection of polystyrene in environmental matrices," *Talanta*, vol. 292, p. 127934, Sep. 2025, doi: 10.1016/J.TALANTA.2025.127934.

[54] B. Chaisrikhwun, S. Ekgasit, and P. Pienpinijtham, "Size-independent quantification of nanoplastics in various aqueous media using surfaced-enhanced Raman scattering," *J Hazard Mater*, vol. 442, p. 130046, Jan. 2023, doi: 10.1016/J.JHAZMAT.2022.130046.

[55] T. Lan, H. Deng, T. Liu, X. Yu, Y. Du, and M. Huang, "In-situ SERS detection strategy based on electric charge adsorption between nanoparticles formed with an effective hetero-charged electric field for detecting polystyrene nanoparticle in aqueous solution," *Sens Actuators B Chem*, vol. 406, p. 135366, May 2024, doi: 10.1016/J.SNB.2024.135366.

[56] M. Liu *et al.*, "Heterostructured organic/MoS2 nanowall with synergistic SERS enhancement enabling direct and sensitive detection of contaminants," *Sens Actuators B Chem*, vol. 401, p. 135007, Feb. 2024, doi: 10.1016/J.SNB.2023.135007.

[57] E. P. C. Lai, A. Onomhante, A. Tsopmo, and F. Hosseinian, "Determination of polystyrene nanospheres and other nanoplastics in water via binding with organic dyes by capillary electrophoresis with laser-induced fluorescence detection," *Talanta*, vol. 284, p. 127265, Mar. 2025, doi: 10.1016/J.TALANTA.2024.127265.

[58] S. Xiao, A. Filippini, M. Casadei, G. Caracciolo, L. Digiacomo, and A. Rossetta, "Fast and portable fluorescence lifetime analysis for early warning detection of micro- and nanoplastics in water," *Environ Res*, vol. 244, p. 117936, Mar. 2024, doi: 10.1016/J.ENVRES.2023.117936.

[59] L. Xiong *et al.*, "ZIF-8 functionalized S-tapered fiber-optic sensor for polystyrene nanoplastics detection by electrostatic adsorption," *Talanta*, vol. 275, Aug. 2024, doi: 10.1016/j.talanta.2024.126168.

[60] H. Li *et al.*, "Operando on-line monitoring of nanoplastics in real environmental water samples enabling an optical microfiber Mach-Zehnder interferometer," *J Environ Chem Eng*, vol. 12, no. 6, p. 114651, Dec. 2024, doi: 10.1016/J.JECE.2024.114651.

[61] Y. Lu, T. Ji, W. Xu, D. Chen, P. Gui, and F. Long, "Rapid, sensitive, and non-destructive on-site quantitative detection of nanoplastics in aquatic environments using laser-backscattered fiber-embedded optofluidic chip," *J Hazard Mater*, vol. 479, p. 135591, Nov. 2024, doi: 10.1016/J.JHAZMAT.2024.135591.

[62] F. Hu, T. Cai, R. Wang, J. Tian, and H. Peng, "A single-atom nanozyme-enabled strategy for rapid, visual, and real-time detection of polystyrene nanoplastics in water," *J Environ Chem Eng*, vol. 12, no. 6, p. 114541, Dec. 2024, doi: 10.1016/J.JECE.2024.114541.

[63] H. Zhou, W. Cai, J. Li, and D. Wu, "Visual monitoring of polystyrene nanoplastics < 100 nm in drinking water based on functionalized gold nanoparticles," *Sens Actuators B Chem*, vol. 392, p. 134099, Oct. 2023, doi: 10.1016/J.SNB.2023.134099.

[64] M. Lu *et al.*, "Real-time and sensitive detection, recognition, and removal of nanoplastics in water based on a BaTiO3-PDMS liquid-solid TENG," *Appl Mater Today*, vol. 44, p. 102738, Jun. 2025, doi: 10.1016/J.APMT.2025.102738.

[65] L. Mou, Q. Zhang, R. Li, Y. Zhu, and Y. Zhang, "A powerful method for In Situ and rapid detection of trace nanoplastics in water—Mie scattering," *J Hazard Mater*, vol. 470, p. 134186, May 2024, doi: 10.1016/J.JHAZMAT.2024.134186.

[66] J. L. Gole, "Increasing energy efficiency and sensitivity with simple sensor platforms," *Talanta*, vol. 132, pp. 87–95, Jan. 2015, doi: 10.1016/J.TALANTA.2014.08.038.

[67] X. Campman, P. Behn, and K. Faber, "Sensor density or sensor sensitivity?," *The Leading Edge*, vol. 35, no. 7, pp. 578–585, Jul. 2016, doi: 10.1190/TLE35070578.1.

[68] L. Shi, Z. Ma, W. Qu, W. Zhou, Z. Deng, and H. Zhang, "Hierarchical Z-scheme Bi2S3/CdS heterojunction: Controllable morphology and excellent photocatalytic antibacterial," *Appl Surf Sci*, vol. 568, p. 150923, Dec. 2021, doi: 10.1016/J.APSUSC.2021.150923.

[69] X. Li, J. Guan, H. Jiang, X. Song, P. Huo, and H. Wang, "rGO modified R-CeO2/g-C3N4 multi-interface contact S-scheme photocatalyst for efficient CO2 photoreduction," *Appl Surf Sci*, vol. 563, p. 150042, Oct. 2021, doi: 10.1016/J.APSUSC.2021.150042.

[70] M. Thompson, S. L. R. Ellison, and R. Wood, "Harmonized guidelines for single-laboratory validation of methods of analysis (IUPAC Technical Report)," *Pure and Applied Chemistry*, vol. 74, no. 5, pp. 835–855, Jan. 2002, doi: 10.1351/PAC200274050835/MACHINEREADABLECITATION/RIS.

[71] International Conference on Harmonization (ICH) of Technical Requirements for the Registration of Pharmaceuticals for Human Use, Validation of analytical procedures: Text and Methodology. ICH-Q2B, Geneva; 1996.

[72] J. Chen *et al.*, "2D MOF Nanosensor-Integrated Digital Droplet Microfluidic Flow Cytometry for In Situ Detection of Multiple miRNAs in Single CTC Cells," *Small*, vol. 18, no. 32, p. 2201779, Aug. 2022, doi: 10.1002/SMLL.202201779.

[73] H. V. Sezgin, Y. Dilgin, and H. İ. Gökçel, "Adsorption and deposition-assisted anodic stripping voltammetry for determination of antimony(III) in presence of hematoxylin on glassy carbon electrode," *Talanta*, vol. 164, pp. 677–683, Mar. 2017, doi: 10.1016/J.TALANTA.2016.10.103.

[74] G. Gauglitz, "Analytical evaluation of sensor measurements," *Anal Bioanal Chem*, vol. 410, no. 1, pp. 5–13, Jan. 2018, doi: 10.1007/S00216-017-0624-Z/FIGURES/11.

[75] G. Alberti, C. Zanoni, L. R. Magnaghi, and R. Biesuz, "Gold and Silver Nanoparticle-Based Colorimetric Sensors: New Trends and Applications," *Chemosensors 2021, Vol. 9, Page 305*, vol. 9, no. 11, p. 305, Oct. 2021, doi: 10.3390/CHEMOSENSORS9110305.

[76] M. Zahran, Z. Khalifa, M. A. H. Zahran, and M. Abdel Azzem, "Recent advances in silver nanoparticle-based electrochemical sensors for determining organic pollutants in water: a review," *Mater Adv*, vol. 2, no. 22, pp. 7350–7365, Nov. 2021, doi: 10.1039/D1MA00769F.

[77] B. Wiley, Y. Sun, B. Mayers, and Y. Xia, "Shape-Controlled Synthesis of Metal Nanostructures: The Case of Silver," *Chemistry – A European Journal*, vol. 11, no. 2, pp. 454–463, Jan. 2005, doi: 10.1002/CHEM.200400927.

[78] L. Xu, Y. Y. Wang, J. Huang, C. Y. Chen, Z. X. Wang, and H. Xie, "Silver nanoparticles: Synthesis, medical applications and biosafety," *Theranostics*, vol. 10, no. 20, pp. 8996–9031, 2020, doi: 10.7150/THNO.45413.

[79] P. Nie, Y. Zhao, and H. Xu, "Synthesis, applications, toxicity and toxicity mechanisms of silver nanoparticles: A review," *Ecotoxicol Environ Saf*, vol. 253, p. 114636, Mar. 2023, doi: 10.1016/J.ECOENV.2023.114636.

[80] P. Li *et al.*, "A preliminary study of the interactions between microplastics and citrate-coated silver nanoparticles in aquatic environments," *J Hazard Mater*, vol. 385, Mar. 2020, doi: 10.1016/j.jhazmat.2019.121601.