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Review Paper:

Potential of wastewater quality assessment using electronic sensors: A review

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Abstract

Untreated wastewater and improper wastewater treatment from domestic and industrial sources continue to degrade water quality around the globe. The greatest challenge currently lies in shifting our perspective on wastewater, aiming to perceive it not merely as a problem but as a potential solution. Several challenges have limited wastewater monitoring and assessment. These limitations include real-time monitoring and aging infrastructure, which can impact the accuracy, efficiency and reliability of the obtained information. These conventional assessment methods are unable to handle the increasing volume and complexity of contaminants in modern wastewater, resulting in poorly treated wastewater. To address this issue, an electronic sensor has been introduced to overcome such crises, providing a better assessment of wastewater quality. Electronic sensors offer a real-time and efficient means to evaluate various parameters in wastewater, providing valuable insights into the composition and potential environmental impact. The potential of wastewater quality assessment using electronic sensors represents a promising avenue in modern environmental monitoring.

This innovative approach allows for continuous and automated monitoring, enabling timely detection of changes in water quality. The utilization of electronic sensors in wastewater assessment holds the potential to enhance our understanding of pollution sources, to facilitate rapid responses to environmental challenges and to contribute to the sustainable management of water resources. In this review, a comprehensive study was performed on electronic sensors to evaluate their physical and chemical properties, as well as a microbial analysis for wastewater quality assessment. Possible challenges and future directions for their development have also been investigated critically. This study will assist future research on electronic sensors which will be highly important for sustainable wastewater assessment.

Keywords: Wastewater, Electronic sensor, Physical properties, Chemical properties, Microbial analysis.

Introduction

Wastewater, an inevitable by-product of human activities and industrial processes, poses significant challenges to environmental sustainability, public safety and health[29,36]. This is due to the direct relationship between wastewater quality and the well-being of communities in terms of safe drinking water and healthy environments. Wastewater treatment is obligatory in Malaysia under the Environmental Quality Act (EQA) 1974. The EQA establishes the legal framework for environmental protection and pollution control in Malaysia, which includes provisions that mandate the treatment of wastewater before being discharged into water bodies. The key aspects of the EQA related to wastewater treatment include the regulatory framework, discharge permits, water quality standards, environmental impact assessment (EIA) and penalties for non-compliance[6].

The EQA empowers regulatory authorities such as the Department of Environment (DOE) to set the water quality standard, which defines the permissible levels of pollutants in water bodies. Similar to EQA, the United States Environmental Protection Agency (U.S. EPA) is responsible for the protection of human health and the environment which plays a significant role in setting and enforcing regulations related to wastewater treatment and pollution control. Both the EQA and the U.S. EPA shared similar objectives with respect to the overarching goal of safeguarding the environment and public health through effective wastewater treatment. With both agencies emphasizing the paramount significance of wastewater treatment policies, underscoring the imperative nature of adhering to proper wastewater treatment practices is necessary to safeguard environmental quality and public health.

Wastewater can be categorized into several types depending on its origin, composition and characteristics including municipal wastewater, industrial wastewater, domestic wastewater, agricultural wastewater and septic tank effluent. Wastewater discharges into water sources such as rivers and streams, lakes and reservoirs, oceans and groundwater can compromise the quality of drinking water supplies[18,29]. Contaminants from inadequately treated wastewater such as chemicals, heavy metals and pathogens, may enter drinking water sources, posing health risks to the consumer[3,17]. Apart from that, poorly treated wastewater can lead to the spread of waterborne diseases, particularly wastewater containing

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pathogens[18]. Contaminated water resources pose a direct risk to public health, causing diseases such as gastroenteritis and chlorella[29].

The high nutrient pollution such as nitrogen and phosphorus in wastewater[23], can lead to harmful algal blooms in water bodies. In some cases, certain algae can produce toxins, affecting human health when ingested. Recognizing the relationship between wastewater quality and public safety and health emphasizes the importance of effective wastewater treatment practices, proper sanitation infrastructure and robust regulatory measures to safeguard water resources and protect human well-being[18]. Public health initiatives often emphasize the need for clean and safe water sources to prevent water-related diseases and to ensure community health.

Current wastewater assessment practices face several challenges, along with the increasing population density and industrial activities[29,32]. These challenges can vary across globes and depend on several factors such as regulatory framework and technological infrastructure. The most common problems are primarily associated with the aging infrastructure. The traditional methods of wastewater analysis often involve time-consuming laboratory procedures, not to mention inconvenient in-situ measurements such as pH measurement via pH meter, presenting limitations in terms of frequency, cost and the ability to provide real-time data[40]. Many wastewater treatment plants are equipped with aging infrastructure that is unable to accommodate the increasing volume and complexity of contaminants in modern wastewater, resulting in poorly treated wastewater[46].

Effective wastewater management necessitates comprehensive assessment tools to monitor its quality, to identify pollutants and to ensure adherence to regulatory standards[18]. In recent years, electronic sensors have emerged as powerful instruments in the field of wastewater quality assessment, offering real-time, accurate and cost-effective solutions[40]. Electronic sensors have revolutionized the approach to wastewater quality assessment by enabling continuous and on-site monitoring of key parameters. These sensors leverage various technologies such as electrochemical, optical and piezoelectric principles, to detect and quantify a wide range of contaminants in wastewater.

The potential of electronic sensors in wastewater quality assessment lies in their ability to address critical challenges faced by conventional methods. These sensors provide rapid and precise measurements, allowing for timely response to variations in wastewater composition. The continuous monitoring capability facilitates the generation of high-frequency data, offering a more comprehensive understanding of temporal variations and potential pollution events. Electronic sensors empower wastewater treatment facilities and regulatory bodies with the means to implement proactive and targeted interventions, optimizing resource utilization and minimizing environmental impact.

Several key parameters monitored by electronic sensors include chemical oxygen demand (COD), biological oxygen demand (BOD), nutrient levels (nitrogen and phosphorus, in particular), pH, conductivity, heavy metals, toxic compounds and pathogen detection. Electronic sensors offer real-time measurements of COD and BOD, crucial indicators of organic pollution in wastewater. This information aids in evaluating the efficiency of biological treatment processes and assessing the overall health of aquatic ecosystems. Monitoring nitrogen and phosphorus levels is essential for preventing nutrient imbalances in water bodies which can lead to eutrophication[18]. Electronic sensors provide continuous data on nutrient concentrations, supporting efficient nutrient removal strategies.

Changes in pH and conductivity are indicative of alterations in the chemical composition of wastewater. Electronic sensors enable the constant monitoring of these parameters contributing to the maintenance of optimal conditions for biological treatment processes. Furthermore, electronic sensors with selective sensors for heavy metals and toxic compounds enable swift responses to potential contaminant spills and ensure compliance with regulatory limits. Advanced electronic sensors incorporating molecular biology techniques can detect and can quantify pathogens in wastewater. This capability is crucial for assessing public health risks and implementing appropriate disinfection measures.

Integrating electronic sensors into wastewater quality assessment represents a transformative leap toward efficient and sustainable water management practices. The continuous monitoring, real-time data acquisition and versatility of these sensors empower investors to make informed decisions, implement timely interventions and safeguard both environmental and public health. This exploration of the potential of electronic sensors in wastewater quality assessment heralds a new era in smart and responsive wastewater treatment strategies. Thus, this review aims to provide information on the use of electronic sensors for wastewater treatment to ensure sustainable wastewater assessment.

This review will discuss the physical and chemical properties of the wastewater with regard to their respective electronic sensors to provide insight into how the sensors operate followed by the microbial analysis. The advantages, challenges and future directions for electronic sensor application in wastewater assessment have also been critically addressed.

Working Principle of Electronic Sensor

Electronic sensors for physical properties are devices that use electronic components to measure and detect various physical characteristics in wastewater. These sensors convert physical signals into electrical signals, allowing for accurate and efficient measurement of different properties. Electronic sensors contribute to a comprehensive assessment of physical properties in wastewater such as turbidity, temperature, color, taste and odor, suspended solids and heavy metals. This holistic approach enhances our understanding of the dynamic nature of wastewater and aids in effective management strategies.

In today's environmental framework, we are typically looking at six main parameters that the discharge limits are focused on: Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), Biological Oxygen Demand$_5$ (BOD$_5$), Total Nitrogen (Total-N), Total Phosphorous (Total-P) and Heavy Metals. To be able to understand how to reduce and control these parameters, we first need to do understand each parameter.

(1) Measurement of TSS: Remote Sensing (RS) applications involving satellite sensors have emerged as a viable alternative in wastewater quality assessments[1]. This method employs images and their spectral properties as inputs and then deep learning analysis, statistical models and machine learning are used to extract valuable insights. The methods employed for retrieving Water Quality Parameters (WQPs) measurements are contingent upon the optical properties of inland water bodies. TSS, as an optically active parameter, contrasts with Total Dissolved Solid (TDS), which exhibits optical inactivity characterized by a low signal-to-noise ratio. The detection of TDS in the visible, near-infrared and infrared bands can be attributed to processes typically coinciding with changes in TDS affecting an optically active WQP.

Satellite sensors exhibit varying sensitivity to different TSS concentrations, demonstrating a positive correlation between red band reflectance and TSS[58]. However, as TSS reaches a certain level, the reflectance stabilizes or remains constant. Furthermore, distinct optical characteristics among open ocean, coastal and inland water bodies lead to variations in TSS-sensitive bands. Inland waters, particularly, showcase greater optical heterogeneity and complexity compared to open ocean and estuary coastal waters. This complexity stems from differences in phytoplankton types such as diatoms or cyanobacteria, which vary between estuaries, coasts and locations like Hedi Reservoir. These diverse phytoplankton types contribute to distinct spectral properties in the water.

(2) Measurement of heavy metal: A biosensor finds applications in various fields including agriculture, food quality control, medicine, the military and environmental process control[39]. They provide rapid information on pollution sites, which is crucial for environmental monitoring. A biosensor is an analytical device that incorporates immobilized biological material in direct contact with a compatible transducer, transforming biochemical signals into measurable electrical signals. Specific analyte recognition is facilitated by biomolecules while the physicochemical converter generates an electrical output signal. The direct electron transfer approach from the recognition element to the electrode has been found to reduce the chances of interference[10]. The advantage of using biosensors is their mobility and compactness, enabling *in situ* measurement of pollutant concentrations without additional sample preparation. Additionally, biosensors can sense specific compounds such as compound toxicity.

The optical fiber sensor, with its distinct advantages of small size, resistant to electromagnetic interference, chemical inertness and capable for remote and real-time monitoring, has emerged as an ideal platform for detecting heavy metal ion concentrations[57]. There are at least five main assessment methods: the optical absorbance method, modal interference method, fiber grating method, plasmonic method and fluorescence method. The sensing mechanism for the optical absorbance method is that the changes in light intensity due to different concentrations of heavy metal ions will contribute to different optical absorption. Constructive and destructive interference for two or more light beams is employed as a measurement principle for the modal interference method.

The different concentrations of heavy metal ions will lead to the different phase differences between two or more beam lights and they will be combined as constructive or destructive interference. Meanwhile, when the effective refraction index of fiber grating is changed due to the wastewater environment, it will lead to changes in resonance wavelength. The difference in resonance wavelength between normal and wastewater environments is beneficial for extracting the properties of the wastewater. The plasmonic method has almost similar principles to the fiber grating method where the plasmonic method utilizes the changes of resonance angle or resonance wavelength due to plasmon wave incident into the sensor system.

The fluorescence effect is employed in the fluorescence method where the fluorescence signals will differ based on the concentration of heavy metal ions. The signals might change in terms of intensity, spectral position and even lifetime. An ultramicro interdigital electrode array chip (UIEA) was designed and fabricated using Micro-Electro-Mechanical Systems (MEMS) technology and it became one of the potential systems to determine heavy-metal ions[53]. The electrodes are used to collect current differences based on the concentration of heavy metal ions.

(3) Measurement of temperature: Wastewater temperature data is beneficial for assessing wastewater quality by estimating sediment accumulation. Sediment deposits are potentially measured by analyzing the differences in sediment-bed temperature using a PT100 temperature sensor[42]. Following the establishment of wastewater and sediment-bed temperature time series, features were extracted from the temperature series using the local maxima and minima (local max/min method) and harmonic features (dynamic harmonic regression method). The outcomes of both methods were leveraged to develop two data-driven models linking features of daily temperature patterns to the sediment thickness specified in the sediment bed temperature simulations. To assess the performance of the data-driven models, temperature time series were segmented and tested.

On the other hand, the DS 18B20 sensor could be used to gauge wastewater temperature at the treatment plant's inlet and pumping stations. The NodeMcu Esp8266 module is programmed to receive the measured temperature data. Subsequently, the collected data encompassing wastewater parameters (temperature and pH) from pumping stations to treatment plants is transmitted to a database server[45].

(4) Measurement of color: Accurate and real-time wastewater characterization used a restricted portion of the visible spectrum. The COD, BOD_5, TSS, TN and TP predictions are based on wavelengths of seven different colors and yield an impressive R^2 of 80–85%. This cost-effective, high-precision wastewater monitoring method employs LED spectrophotometry, allowing for real-time monitoring of pollutant levels at a reduced cost [8].

(5) Measurement of taste and odor: Electronic nose systems, utilizing gas sensors, play a crucial role in analyzing and categorizing gas mixtures, specifically distinguishing components within a given mixture[13]. The multivariate data from these sensors allow the prediction of parameters associated with wastewater quality such as COD, ammonia nitrogen (AN), TN and TP, as well as other environmental parameters linked to air and odor pollution. The monitoring of wastewater treatment plants is envisioned as a prospective application of e-noses, involving the classification of samples from different treatment stages, identification of sources, or assessment of odor concentrations.

The capability of gas sensor arrays to differentiate contaminants makes electronic noses well-suited for detecting unusual situations in wastewater treatment plants that could lead to failures. Table 1 summarizes the electronic sensors for sensing physical properties in wastewater with respect to their physical properties such as TSS, heavy metal, temperature, color, taste and odor.

Electronic sensor for chemical properties

Electronic sensors for chemical properties are devices designed to detect and measure specific chemical characteristics in a given environment. These sensors utilize various technologies to convert chemical signals into electrical signals for analysis. Electronic sensors play a crucial role in accurately measuring chemical properties in wastewater such as dissolved oxygen (DO), chemical oxygen demand (COD), biological oxygen demand (BOD), pH levels, concentrations of specific ions, salinity and the presence of various contaminants. This precision is essential for ensuring compliance with environmental standards and regulations.

(1) Measurement of dissolved oxygen (DO): Dissolved oxygen (DO) denotes the amount of oxygen dissolved in one water unit. The escalating levels of contaminants such as nitrogen and phosphorus, have resulted in a significant issue within the domain of wastewater quality. Accurate measurement of the dissolved oxygen levels in wastewater is crucial in guaranteeing that the effluent does not harm the environment. Polarographic sensors, consisting of a cathode and anode, are commonly employed to measure the concentration of DO[56]. Zhang et al[56] found that including a luminescent DO sensor in an automated oxygen supply device (AOSD) system can enhance the removal of pollutants from wastewater. The work enhanced the utilization of traditional polarographic dissolved oxygen (DO) sensors in the context of wastewater treatment.

The experiment utilized a luminous DO sensor of the HACH 5790018 LDO model and a polarographic DO sensor of the Mettler Toledo Pro6050 Polarographic Oxygen Sensor model[56]. In another study, Er et al[15] introduced a dissolved oxygen optical sensor that utilizes platinum octaethylporphyrin (PtOEP) immobilized in a polydimethylsiloxane (PDMS) membrane. The optical sensor developed in the study used the fluorescence quenching method as its underlying concept. The measurement principle relies on fluorescence lifetime detection, determined by the phase difference between an excitation light signal and a fluorescence signal[34].

Table 1
Summary of electronic sensors for sensing physical properties in wastewater

Physical Properties	Electronic Sensor
Total Suspended Solids (TSS)	Satellite sensor
Heavy Metal	Biosensor sensor
	Optical fiber sensor
	Ultramicro interdigital electrode array
Temperature	PT100 temperature sensor DS 18B20 temperatur sensor
Color	LED spectrophotometer
Taste and Odor	Gas sensor

(2) Measurement of chemical oxygen demand (COD): Chemical oxygen demand (COD) is a significant metric used to assess the extent of water pollution resulting from chemical properties whether organic or inorganic. Mohammadi et al[35] developed a microwave-microfluidic sensor to monitor organic pollutants in wastewater discharges.

The sensor was constructed using a small double-ring resonator that was combined with a 3D-printed microfluidic channel. It operated at 4.5–4.6 GHz with a 120-quality factor. The sensor that was designed to follow the COD standard has become a crucial parameter to be observed in wastewater treatment. The sensor measures the concentration of potassium hydrogen phthalate, which can range from 50 to 800 mg/L as COD. The test solution for the developed sensor was made with concentrations ranging from 50–800 mg/L equivalent COD concentration to cover the range of standards recommended in Standard Methods for the Examination of Water and Wastewater Method 5220[43].

Wang and Valle[52] efficiently quantified agricultural wastewater COD by employing nanoparticle-enhanced voltametric sensors and an electronic tongue. The sensor development system was assisted by chemometric processing. The data-processing algorithms implement principal component analysis (PCA). The electronic tongue array used four copper, copper oxide and nickel copper alloy electrodes. The voltametric array quantified and qualitatively analyzed river water samples using a Nafion film-covered electrodeposited CuO/Cu electrode and copper, copper oxide and nickel copper alloy nanoparticle-graphite-epoxy composite electrodes. COD levels were estimated using the calibration equation based on the linear relationship between COD and current intensity. PCA was utilized on voltammogram profiles to evaluate the primary component of a polluted water sample to determine its degradability[52].

Duan et al[14] measured COD in urban wastewater treatment plants (UWWTP) using an electrochemical sensor. The electrochemical sensor used sol-gel material synthesis and photolithography/dry etching to make thin-film carbon electrodes on Si/SiO_2 substrates. Three-electrode electrochemical cells with a planar configuration were employed in the COD sensor. The electrode was made by electropositing copper nanoparticles (Cu NPs) under regulated potentiostatic circumstances. As a result, a linear range of 670 $mg \cdot L^{-1}$ O_2 and a detection limit of 30 mg·L-1 O2 were achieved. The data are based on three UWWTP samples from different locations[14].

(3) Measurement of biological oxygen demand (BOD): Biological oxygen demand (BOD), also referred to as biochemical oxygen demand (BOD), is a commonly used measure for assessing the quality of water sources. It quantifies the oxygen needed to break down organic substances in a water sample chemically. BOD employs a highly concentrated population of microorganisms to measure integral indicators accurately[44]. Kurbanalieva et al[28] developed a BOD sensor using electroactive biofilms of activated sludge on a graphite-paste electrode enhanced with carbon nanotubes. The working principles of the developed sensor are based on charge transfer in electroactive biofilms, which were examined using cyclic voltammetry and electrochemical impedance spectroscopy. The cyclic voltammetry method was used to measure the rate constants of microbe contact with the extracellular electron carrier (0.79 ± 0.03 dm3$(g\ s)^{-1}$) and electron transfer (0.34 ± 0.02 cm s^{-1}). The reported results showed that modifying the carbon nanotube (CNT) electrode surface permits electroactive biofilms with excellent detection[28].

Pattnaik et al[41] implemented machine learning techniques to develop BOD soft sensors. The study investigated the accuracy, prediction time and design of a predictive BOD soft sensor model for the Internet of Things (IoT). The BOD concentration can be determined by measuring the concentration of degradable organic matter in terms of the total oxygen needed for its oxidation. The study used an offline laboratory method wherein the initial dissolved oxygen (DO) level in the collected sample was measured (DO1). The sample is then stored in a darkroom at a temperature of 20°C. After five days, the DO value is measured again (DO_5) and the BOD can be computed based on the 5-day period as described in eq. (1):

$$\mathrm{BOD}_5 = \frac{DO_1 - DO_5}{P} \tag{1}$$

where ‘P’ is a volumetric fraction of wastewater (sample volume divided by container volume). Due to the 5-day test interval, BOD5 is impractical for real-time water quality monitoring[41].

Tardy et al[49] used the approach of single-chamber air cathode microbial fuel cells (MFCs) in their biosensor to measure BOD using suspended and/or slowly biodegradable organic content. Batch sample injection, continuous cell voltage monitoring and total charge (Q) calculation during organic content biodegradation are used for analysis. Acetate and peptone samples with only soluble, biodegradable substrates, corn starch, milk samples with suspended and colloidal organics and residential and brewery wastewaters were studied. As a result, linear regression fitted to real wastewater Q vs. BOD_5 [16] data points yielded R^2 values > 0.985. The sample composition determined the measurement time which ranged from 1 to 4 days. The proposed technique might be used to construct on-site automatic BOD sensors for real wastewater samples[49].

(4) Measurement of pH level: Nigam et al[37] employed a pH meter (Hanna Instruments, USA) to measure hexavalent chromium (Cr (VI)) in tannery wastewater. The study also mentioned that India annually discharges 9,420,000 cubic meters of tannery wastewater (TWW). Chromium has two stable oxidation states: Cr (III) and Cr (VI). The study stated that Cr (VI) is carcinogenic, mutagenic and hazardous to living organisms. Valian et al[51] found that electrolyte-insulator-semiconductor pH sensors have the potential to characterize or detect mefenamic acid drugs from pharmaceutical wastewater. Manjakkal et al[31] reviewed metal oxide (MOx)-based electrochemical pH sensors to be used in sensing any pH changes in wastewater. The study found that the sensitive electrodes (SE), which are a crucial component of electrochemical pH sensors, are mainly composed of glass membrane electrodes, MOx, metal/MOx, polymers and carbon. An analysis of the SEs derived from these materials revealed that ion-sensitive MOx garnered significant attention, particularly those based on micro- and nanostructures.

(5) Measurement of ammonia: The wide range of real-time ammonium measurements for monitoring and control has garnered interest. Cecconi et al[9] evaluated ion-selective electrode (ISE) ammonium sensors throughout the year under different operating circumstances during diurnal and seasonal changes. Three ISE-ammonium sensors were put in an activated sludge aeration tank. One probe was placed at the end of the aeration tank to test the sensor in low-range conditions (<1 mg N-NH_4^+ per L). Two standard solutions containing 1 mg N-NH_4^+ per L, 5mg K+ per L, 10 mg N-NH_4^+ per L and 50 mg K^+ per L were used to calibrate the ammonium and potassium electrodes simultaneously. Both standard solutions contained 0.1 mol L^{-1} lithium acetate dihydrate, which increased ionic strength and influenced sensor voltage measurement.

The sensor is submerged in wastewater and compared to a grab sample collected next to the sensor through lab analysis. Figure 1 shows the basic physical operation of the ISE-NH_4^+ sensor[9]. A tilted fiber Bragg grating (TFBG) sensor surface-functionalized with a thin coating of PVDF-BPB was proposed for wastewater ammonium detection[30]. Ma et al[30] modified the PVDF-BPB film's surface structure with ammonium which affected the TFBG cladding modes' extinction ratio. Ammonium content correlated with bromophenol blue reaction strength. In the study, the integral areas of all cladding modes vs reaction time quantifies ammonium concentration were calculated. Experimental results showed the proposed sensor could detect ammonium linearly from 0.1 to 10 mg/L in 5 minutes[30].

(6) Measurement of salinity: Salinity refers to the degree of saltiness or concentration of salt dissolved in a body of water, known as saline water. De Carlo et al[12] studied the application of an electrical resistivity tomography (ERT) sensor in monitoring soil salinity when brackish wastewater was used for maize irrigation. The salinity of the soil mixed with brackish wastewater was tested based on the electrical conductivity value. Ahmad et al[2] developed a floating sensor system, known as the Lagrangian sensor system, to detect several parameters in urban wastewater, one of which is monitoring the salinity level. The system can log and transmit spatially distributed global positioning systems (GPS) to provide real-time data monitoring. The study used an electrical conductivity (EC) sensor to monitor the salinity level. The float sensor was designed using a printed circuit board (PCB).

(7) Measurement of hardness: Bhattacharjee et al[7] designed a fluidic colorimetric sensor for detecting the water hardness in sewage. Calmagite, a metal ion indicator, undergoes a color shift in the presence of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions at pH 10, resulting in a wine-red solution. The proposed sensor prototype was fabricated using 3D printing technology, incorporating a passage within its structure to contain a water sample (sewage) securely. The detection of water hardness is determined by visually inspecting the color change of the sample and measuring the voltage change that occurs when calmagite and ethylenediaminetetraacetic acid (EDTA) are mixed with the sample.

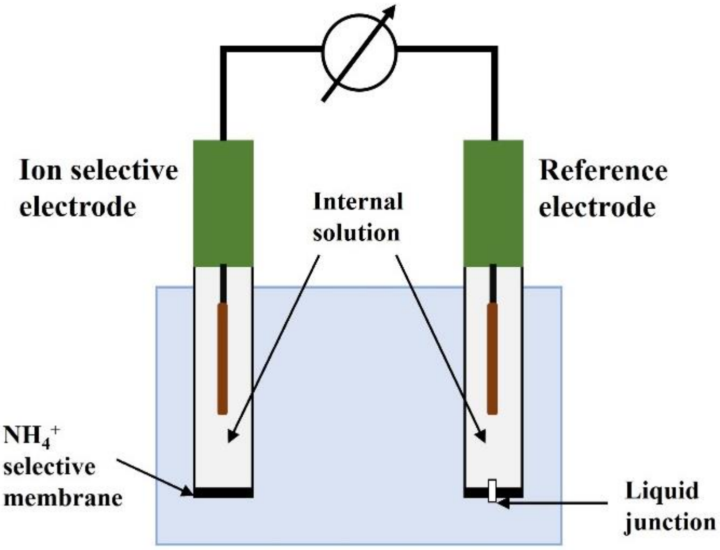

Figure 1: Basic physical operation of the ISE-NH4+ sensor

In another study, Amineh et al[5] reported a microwave cylindrical resonant cavity sensor for water hardness. The experiment used a 2.5 GHz microwave cavity resonator conceived and built locally to measure calcium hardness content and dielectric characteristics in heat exchanger cooling water non-invasively. The calcium-ion content-dependent sample solution was analyzed using electric dipole moment theories. $CaCl_2$ in deionized water created artificial water hardness for analysis. The sample was centrally placed in the TM_{010}-mode electric field of the resonant cylindrical cavity[50].

(8) Measurement of organic compounds: Aliqab et al[4] designed a graphene metasurface organic material sensor (GMOMS) for sensing the existence of organic compounds in wastewater. The GMOMS sensor design employs a circular spring ring resonator (CSRR) including a gap and a circular structure (CS), to achieve high sensitivity. The CSRR and CS combination function as a resonator that oscillates at a precise frequency in the presence of organic compound molecules. The gap between the CSRR and CS permits the passage of molecules, enhancing the sensitivity of the sensor[4].

Another study found that a functionalized carbon nanotube-coated screen-printed electrode (CNT-SPE) modified with –COOH and $-NH_2$ functional groups can detect the volatile organic compound 1-cyclohexyl-2-pyrrolidone (CHP) in a bio electrochemical system (sensing system) inoculated with *Escherichia coli* and supplemented with 2-hydroxy-1,4-naphthoquinone (2-HNQ)[22]. The addition of CHP decreased the bio electrochemical system’s current output, allowing quick CHP concentration monitoring. The H_2N-CNT-SPE performed best under optimum circumstances with a limit of detection (LOD) of 0.4 mg/L^{-1}. There was relatively negligible inorganic and organic interference with the proposed sensor[22].

(9) Measurement of metals: Environmental samples contain toxic heavy metals, which have become a significant issue. Copper, an example of a metal ion, is widely used in numerous industrial applications. Srinivasan and Deivasigamani[48] developed a porous polymer-based monolithic solid-state optical sensor for detecting Cu (II) ions with high selectivity and sensitivity. The intertwined meso- and macro-porous channels with tunable diffusion layers form the porous monolith. 4-butyl-N-((1,3-dioxo-1H-benzo[de]isoquinolin-2(3H)-yl) carbamothioyl) benzamide (BDICB) and 4-butyl-N-(2-(thiophene-2-carbonyl) hydrazine-1-carbonothioyl) benzamide (BTHCB) chromoionophoric probes serve as solid-state colorimetric sensors by implementing the bimodal meso-/macro-porous polymer monolithic structure[48].

Kim et al[26] developed high-sensitivity and durable boron-doped diamond (BDD) electrodes for heavy metal ion sensors. Hot-filament chemical vapor deposition (HFCVD) BDD electrode substrate preparation and deposition were optimized in the study.

Table 2
Summary of electronic sensors for sensing chemical properties in wastewater

Chemical properties	Electronic Sensor
Dissolved oxygen (DO)	Integration of luminescent and polarographic DO sensor
	PtOEP-based optical sensor
Chemical Oxygen demand (COD)	Microwave-fluidic sensor
	Integration of nanoparticle-enhanced voltammetric sensor and electronic tongue
	Electrochemical sensor
Biological oxygen demand (BOD)	Electroactive biofilm-based BOD sensor
	BOD soft sensor
	Microbial fuel cells (MFCs)-based BOD sensor
pH level	pH meter
	Electrolyte-insulator-semiconductor pH sensor
	Metal oxide (MOx)-based electrochemical pH sensor
Ammonia	Ion-selective electrode (ISE)-based ammonium sensor
	Tilted fiber Bragg grating (TFBG) sensor
Salinity	Electrical resistivity tomography (ERT) sensor
	Electrical conductivity (EC) sensor
Hardness	Fluidic colorimetric sensor
	Microwave cylindrical resonant cavity sensor
Organic compounds	Graphene metasurface organic material sensor (GMOMS)
	Carbon nanotuve screen-printed elctrode (CNT-SPE)-based biochemical sensor
Metals	Porous polymer-based monolithic solid-state optical sensor
	Boron-doped diamond (BDD) electrode-based sensor

The improved BDD electrode with 8000 ppm doping detected Cd (II), Pb (II) and Cu (II) ions with great accuracy and precision. The result reported that the detection limits for Cd (II), Pb (II) and Cu (II) ions were 0.55 (±0.05), 0.43 (±0.04) and 0.74 (±0.06) µg/L (S/N = 3) respectively. The electronic sensors that can be considered for detecting the chemical properties of wastewater such as DO, COD, BOD, pH level, ammonia, salinity, hardness, organic compounds and metals, are summarized in table 2.

Electronic sensor for microbe analysis

Electronic sensors for microbe analysis in wastewater are basically operated on the principle of quantifying and detecting microorganisms in water samples. These sensors are necessary to monitor water quality, particularly associated with safeguarding drinking water and wastewater treatment. Incorporating electronic sensors for microbe analysis in wastewater streamlines the assessment of microbial content. This efficiency is particularly valuable in understanding the microbiological aspects of wastewater, contributing to better-informed decisions in terms of public health and environmental safety. Electronic sensors can identify the microbial species present in the wastewater, as well as can detect and quantify the microorganisms in wastewater samples. Several electronic sensors for microbe analysis have been developed to aid in monitoring wastewater. These include fluorescence-based sensors, impedance-based sensors, DNA-based sensors, biosensors and bio electrochemical sensors.

(1) Microbial identification: One of the developed electronic sensors used to identify microbial species is the fluorescence-based sensor. Fluorescence-based sensors are extensively used in wastewater monitoring to characterize pollutants and for microbial population identification[21,25]. Fluorescence-based sensors for microbe analysis are sensors employ the principle of fluorescence for microorganism detection and quantification. This type of sensor uses a specific molecule acting as labels or tags such as antibodies or fluorescent dyes to detect microorganisms. The fluorescent labels are designed to attach to the targeted microorganisms which selectively bind to the microbe of interest, targeting particular DNA sequences, antigens, or proteins on the surface of the microbe. Once labelled, the sample containing microorganisms is exposed to a specific light wavelength known as excitation light, which energizes the fluorescent molecules. The fluorescent emission due to the release of energy in the form of light is a characteristic of the fluorescent labels used and can be detected by a photodetector, which measures the intensity of the fluorescent emitted. The intensity of the fluorescence is directly proportional to the concentration of the microorganisms in the sample.

Due to the critical roles of fluorescence technology in many fields, the technology has been researched widely by many scientists. During recent decades, fluorescent-based sensors have been used to treat wastewater, substituting the traditional biochemical oxygen demand (BOD) indicator[33]. This is due to electronic sensors yielding immediate results using less reagents and being relatively economical with a lower minimum detection limit than absorbance[24]. The fluorescent-based sensor has proven to be an efficient technique for monitoring water quality in surface waters for tracking pollution sources, water treatment process control and optimization[21].

(2) Microbial detection and quantification: Another technology involved in the development of electronic sensors includes microbial detection and quantification. Examples of electronic sensors used to identify and quantify microorganisms include impedance-based sensors, DNA-based sensors, biosensors and bioelectrochemical sensors. The impedance-based sensor is gaining substantial attention in fields related to studying biological species and bacterial biofilm, which led to the introduction of impedance microbiology[19,27]. Impedance-based sensors are biosensors that measure the changes in electrical impedance or resistance caused by the presence of microbes. These sensors are used to detect and quantify microorganisms in water, food and clinical samples. The microorganism comprises of an insulating membrane filled with liquid plasma, which shows dielectric properties.

The structure allows them to behave like electrical capacitors, which store electrical charge when current is applied. The available ions in plasma tend to move toward the cell membrane when exposed to an electric field, creating ion movements and inducing a change in the electric fields[19]. An impedance-based sensor commonly consists of two or more electrodes made from conductive materials that come into direct contact with the sample. Once contacted with the electrode, the sample introduces changes in the electrical impedance of the system. The changes occur due to cell adhesion, electrolyte changes and cell size and density. The adhesion of microorganisms to the electrode surface can create an insulating layer which increases the impedance. The metabolism and growth of microorganisms can alter the conductivity of the surrounding electrolyte which also affects impedance. Microorganisms' size, shape and density can also influence the impedance changes[27].

The electrical impedance of the system is measured continuously during direct contact. The resulting impedance data is then processed and analyzed in real-time. The degree of impedance change is directly proportional to the concentration of microorganisms in the sample. The sensor can quantify the microbial load based on the observed impedance changes. Unlike fluorescent-based sensors, impedance-based sensors work as label-free detectors. This sensor requires no labelled molecules or tags, making the detection easier and cost-effective. Also, the impedance-based sensor can be applied to various microorganisms, compared to the fluorescent-based sensor which is a highly specific sensor. Apart from their application in wastewater treatment, impedance-based sensors can be used in various applications such as microbial growth monitoring in pharmaceutical and biotechnology processes and detecting pathogens in food and clinical samples.

DNA-based sensors are biosensors utilizing DNA or genetic material for the detection and quantification of microorganisms in various samples. These sensors rely on DNA markers or unique genetic sequences of targeted microorganisms for identification and analysis. The mechanism for DNA-based sensors generally starts with the extraction of DNA or RNA from the microorganisms through RNA isolation or DNA extraction procedure. DNA-based sensors are designed to target specific DNA sequences unique to the targeted microorganisms. These DNA sequences are naturally conserved and found in all strains of the target microorganism. Similar to fluorescent-based sensors, DNA-based sensors also use labelled molecules as a marker to the DNA probes, designed to complement the target DNA sequences. The hybridization between DNA probes and target DNA sequences produces a stable duplex, which generates a detectable signal[47].

The signal can be generated through several events such as fluorescence, electrochemical detection and luminescence. The fluorescent signal is emitted when DNA probes bind to the target DNA sequence which can be detected through fluorescence spectroscopy. DNA hybridization can result in changes in the electrical conductivity or impedance of the sensor, which can be measured using electrochemical techniques. Luminescent molecules can be used as markers and their emission intensity changes upon DNA hybridization, allowing for detection[47]. The intensity of the signal is proportional to the concentration of the target microorganisms in the sample. To date, DNA-based sensors are extensively used in various applications such as environmental monitoring and clinical diagnostics.

Biosensors and bioelectrochemical sensors are specific devices used for microbe analysis and often employ biological elements to detect and quantify microorganisms. Biosensors employ biological components such as antibodies, enzymes, DNA, or whole cells to detect microorganisms. In a biosensor designed for microbial analysis, the biological recognition element specifically targets the microorganism[38]. For example, antibodies or DNA probes can be used to recognize and to bind to unique surface markers or genetic material of the target microbe. The interaction between the biological element and the microorganism generates a signal. This signal can be based on various principles such as changes in enzyme activity, binding-induced conformational changes, or chemical reactions triggered by the binding event[11]. The signal generated by the biological element is then transduced into a measurable output. This transduction process typically involves a physical or chemical change that can be detected and quantified. Standard transduction methods include electrochemical, optical and piezoelectric methods. The biosensor detects and analyses the output signal, resulting in quantitative information on the concentration or presence of the target microorganism. Apart from wastewater treatment, biosensors can be used in environmental monitoring as well as biotechnology research.

Bio electrochemical sensors are a subset of biosensors that specifically rely on electrochemical principles to detect and quantify microorganisms. Bio electrochemical sensors use microbial metabolism to generate electrical signals associated with microbial activity. It employs microorganisms such as bacteria to create electrochemical signals in response to the presence of specific analytes. The microorganisms used in this analysis are selected based on their ability to interact with the target microorganisms, in which the production or consumption of specific electroactive molecules occurs when the target microorganisms are present in the system.

Electrochemical changes occur when the biological element interacts with the target microorganisms which may involve electron transfer and changes in redox potential. Bio electrochemical sensors consist of electrodes that are in contact with the biological element. These electrodes capture and amplify the electrochemical signals generated by the microorganism-biological element interaction. The electrochemical signals produced by the interaction are detected and analyzed, providing data on the concentration or presence of the target microorganism. Bio electrochemical sensors are particularly useful in environmental and microbial monitoring as well as in biotechnology and bioenergy applications, where they can provide insights into microbial metabolic activity and the presence of specific microorganisms. They offer the advantage of high sensitivity and real-time monitoring. The summary of the electronic sensors used for microbial analysis is presented in table 3.

Table 3
Summary of electronic sensors for microbial analysis in wastewater

Analysis	Electronic Sensor
Microbial identification	Fluorescence-based sensor
Microbial detection and quantification	Impedance-based sensors
	DNA-based sensors
	Biosensors and bioelectrochemical sensors

(3) Advantages of electronic sensor for microbial analysis: The use of electronic sensors in wastewater treatment offers several advantages particularly in microbial analysis. Electronic sensors provide real-time data for monitoring, making them a perfect tool for continuous water quality monitoring, which enables quick responses to changing conditions in wastewater treatment plants. Moreover, electronic sensors are highly sensitive and can detect an even lower concentration of microorganisms. The high specificity offered by the electronic sensors allows for detecting a specific microbial strain, reducing the probability of false positives or negatives.

In the case of a fluorescent-based sensor, multiple fluorescence labels can be used concurrently to detect various microorganisms in a single sample which reduces not only the time consumption but also the materials. These sensors have shown the ability to achieve high portability and miniaturization and they permit the incorporation of digital technologies such as smartphones and are very relevant in low-resource settings. These rapid sensors have shown the ability to achieve high portability miniaturization and they permit the incorporation of digital technologies such as smartphones and are very relevant in low-resource settings.

More importantly, the analysis through electronic sensors is generally non-destructive which preserves the integrity of the sample for further use analysis or testing. In addition, compared to traditional methods for wastewater monitoring, the use of electronic sensors in wastewater monitoring and treatment offers a profitable bargain due to the reduced labour as well as materials and chemicals consumption for wastewater treatment. Therefore, the use of biosensors for wastewater monitoring could offer more excellent benefits compared to conventional techniques in the detection of bacterial pathogens due to the rapidity of the test, being very sensitive, specific and selective and not to mention laborious which could significantly reduce the associate cost for wastewater treatment apart from being very efficient as compared to the conventional method[38].

Challenges and Future Directions

Despite the extraordinary benefits of using electronic sensors, challenges in their application are inevitable. This is due to the maintenance of the sensor since they may require routine maintenance to ensure accurate measurements. Commercializing the devices for use in wastewater treatment might cost an ample amount, which is one of the significant challenges of advertising biosensors, consequently limiting their wide applications. In addition, some electronic sensors are not resistant to heat due to the presence of heat-sensitive molecules, which cannot be sterilized using heat. The high cost associated with the research and development in electronic sensor fields makes implementing this technology somewhat tricky. This study underlines the need for affordable sensor systems to encourage widespread usage, especially in economically disadvantaged locations.

In the case of gas sensors and electronic noses, the most significant challenge limiting their utilization in environmental applications is the absence of specific regulations for their standardization. The definition and standardization of features and performance for e-nose tools and their application methods are pre-requisites for their widespread adoption[55]. Concerning the sensors, several studies have underscored the issue of stability towards temperature and humidity variations and sensor response drift over time. This study presents potential solutions to these problems using appropriate data processing methods, revealing that electronic nose devices require time-consuming calibrations and re-calibrations and/or sophisticated and complex technology to produce accurate and reliable results.

Despite these challenges, a few commercial e-noses dedicated to environmental monitoring exist. However, primarily due to issues associated with sensor stability, the warranty provided by manufacturers is usually very short (i.e. 12 months) and given the price of these devices, it is often deemed unsatisfactory. In many cases, a malfunctioning sensor cannot be replaced with a new one due to the poor reproducibility of gas sensor manufacturing[20].

Throughout this review, the main challenge for adopting electronic sensors in detecting chemical properties of wastewater is creating a multi-parameter sensor device that can adequately detect DO, COD, BOD, pH, heavy metals, organic contaminants and nutrient levels in wastewater. Real-time monitoring to optimize treatment processes and respond to dynamic wastewater conditions has also become a priority. Another essential factor is sensor system reliability in difficult operational situations, like wastewater treatment plants.

Additionally, calibration is necessary to guarantee a precise measurement of the microbe analysis sensor in which known standards with specific microbial concentrations are needed for calibration. Apart from periodic calibration, quality control is also needed to be performed regularly to maintain the accuracy of the sensor. Furthermore, fouling of the sensor surface by particles in wastewater application is inevitable, which affects the performance of the sensor[24]. Also, interpreting the sensor's data requires expertise since the analysis could be complex and complicated.

Therefore, to counter the challenges faced when using the electronic sensor for wastewater treatment, several future directions are recommended. This includes ongoing research that aims to enhance the robustness of the sensor and reduce fouling issues. Implementing nanotechnology to increase sensor sensitivity, accuracy and selectivity for trace pollutant detection should be considered. Biosensors, for example, which use biological components to detect chemicals, can improve specificity and lessen environmental effects. Integration with the Internet of Things (IoT) and data analytics is highly recommended for more efficient data interpretation and management[40,54]. Data analysis using machine learning and artificial intelligence (AI) algorithms can also dynamically optimize wastewater treatment operations based on sensor inputs.

Developing a portable and field-deployable sensor is advantageous to ease their application in a remote area or an area with poor setup. Advanced wireless sensor networks are also recommended for broad coverage of large treatment facilities and outlying areas. For end-users, user-friendly interfaces simplify sensor data interpretation for informed decision-making. Nevertheless, electronic sensors are undoubtedly beneficial in the innovation of wastewater quality assessment with respect to real-time information which aids in maintaining the efficient wastewater treatment process, thereby contributing to public health and environmental protection. This study emphasizes the necessity of integrating sensor technology with evolving regulatory standards to meet wastewater treatment monitoring and reporting needs. This review explains a roadmap for expanding electronic sensor technology, which could revolutionize smart wastewater management.

Conclusion

The use of electronic sensors for wastewater quality assessment offers the advantage of real-time monitoring, which allows for prompt detection of changes in both physical and chemical properties, enabling quick response to potential environmental risks. Electronic sensors demonstrate adaptability to diverse wastewater sources, making them valuable tools in addressing the unique challenges associated with different wastewater characterizations. The potential for integrating electronic sensors with smart technologies enhances the scalability and accessibility of wastewater quality assessment. This integration facilitates remote monitoring, data sharing and the implementation of smart water management systems. The capability of electronic sensors to swiftly identify and quantify contaminants in wastewater is a critical factor in preventing the release of harmful substances into the environment.

Early detection allows for proactive measures to mitigate potential negative impacts on ecosystems. As technology advances, ongoing research and innovation in electronic sensor technology will further enhance the potential of wastewater quality assessment. Continued collaboration between scientists, engineers and policymakers will contribute to the development of more sophisticated sensor systems and improved methodologies. In conclusion, integrating electronic sensors for wastewater quality assessment presents a promising paradigm shift in environmental monitoring. The combination of real-time monitoring, precise physical and chemical properties analysis and efficient microbe analysis positions electronic sensors as key contributors in sustainable and effective wastewater management practices.

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