American Journal of Nanosciences
2025, Vol. 9, No. 2, pp. 42-52
https://doi.org/10.11648/j.ajn.20250902.12

Research Article

A Review on the Performance of Metal Oxide Nanoparticles in Electrochemical Sensors for Detecting Flavor and Fragrance Compounds

Fatemeh Jalili[1], Abbas Abedfar[1,*], Sepideh Pourvatandoust[2], Fatemeh Abbaszadeh[3]

[1]Department of Food Science & Technology, University of Guilan, Rasht, Iran
[2]Department of Food Science & Technology, Islamic Azad University, Tehran, Iran
[3]Department of Food Science & Technology, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran

Abstract

Metal oxide nanoparticles (MONPs) have been recognized as extremely promising materials in the enhancement of electrochemical sensors, specifically to detect flavor and fragrance compounds. This review dives into the performance of various MONPs, such as Zinc Oxide (ZnO_2), Titanium Dioxide (TiO_2), Manganese Oxide (Mn_3O_4), Nickel Oxide (NiO) and Copper Oxide (CuO), highlighting each of their unique properties that could help develop the sensitivity of flavor and fragrance sensors. Furthermore, this article discusses the synthesis methods of MONPs, their functionalization, and incorporation into sensor platforms. Key electrochemical techniques are examined to illuminate the mechanisms of interaction between MONPs and target analytes. Recent advancements in nanocomposite materials combining MONPs with conducting polymers or carbon-based materials are also considered, showcasing improvements in detection limits and response times. Additionally, the up-and-coming challenges and future directions for the application of MONPs in the realm of flavor and fragrance detection are discussed, emphasizing the need for further research to optimize sensor designs and their peak commercial capability. Future studies should aim to reduce the size of sensors while maintaining or improving their sensitivity and selectivity. This development could lead to the creation of handheld devices for present monitoring of flavor and fragrance compounds in various settings, such as food production and consumer markets. Also, since the combination of machine learning and artificial intelligence into sensor data analysis has been off to a promising direction, by utilizing advanced algorithms, researchers can enhance the interpretation of complex data sets generated by electrochemical sensors. It is hoped that this article brings more attention to these techniques as they meet the current and future needs of food industry. It is hoped that this article brings more attention to these techniques as they meet the current and future needs of food industry.

Keywords

Electrochemical Sensors, Flavor Compounds, Fragrance Detection, Metal Oxide Nanoparticles, Sensor Performance

[*]Corresponding author: a.abedfar@guilan.ac.ir (Abbas Abedfar)

Received: 27 August 2025; **Accepted:** 12 September 2025; **Published:** 10 October 2025

1. Introduction

Metal oxide nanoparticles (MONPs), such as Titanium Dioxide (TiO_2), Aluminum Oxide (AlO_2), and Zinc Oxide (ZnO_2) are established [1] as particles that have one dimension within the nanoscale range (1–100 nm), to say the least. Their distinct properties, make them valuable for various applications, including electronics, medicine, catalysis, environmental cleanup, and energy storage. The high surface-to-volume ratios of these nanoparticles are one of their standout features. This means that a greater amount of their surface area is available for interactions, making them incredibly effective in applications like catalysis, where reactions occur at surfaces. Additionally, their electronic structures can be finely tuned, allowing for adjustments in their conductivity and reactivity. This versatility is a game-changer, especially in areas such as electronics and energy storage, where specific performance characteristics are essential. As we dive deeper into the literature surrounding metal oxide nanoparticles, we can see a growing wave of interest and research focused on these materials. Scientists and engineers are increasingly recognizing their potential, particularly due to their remarkable optical properties and enhanced electrical conductivity when compared to their bulk counterparts. This has led to their widespread use in applications like biosensing and imaging, where accuracy and sensitivity are paramount.

2. Importance of Electrochemical Sensors

Electrochemical sensors play a vital role across many different fields, from biology and environmental science to industry and pharmaceuticals. Their importance is due to several key advantages that make them incredibly valuable tools in our modern world. One of the standout features of these sensors is their remarkable sensitivity. They have the ability to detect even the tiniest traces of substances, which is crucial in various applications [2]. Essentially, the significance of electrochemical sensors stems from their capacity to deliver dependable, rapid, and sensitive analyses, fostering advancements in healthcare, environmental safeguarding, and numerous industrial uses [3]. In addition to their sensitivity, electrochemical sensors provide rapid analytical responses, which is essential for applications that require immediate results, where timely information can influence decision-making and outcomes. These sensors are also user-friendly and cost-effective. They often require simple equipment, the quality that makes them more accessible for routine use in both laboratories and field settings [2, 4]. This availability is further improved by the development of biosensors, a specialized subsection of electrochemical sensors in which they bring extra additional benefits, such as the ability to collect data quickly and directly detect analytes without extensive sample preparation [5]. A typical biosensor consists of three main components: biocomponents, which include enzymes, antibodies, or DNA probes that interact specifically with the target analyte, which convert these biochemical interactions into measurable electrical signals and signal processing systems that interpret these signals into readable form. The versatility in design is another appealing feature thanks to the ability of electrochemical sensors in being tailored in required shape, material, and configuration to meet said specific needs, making them adaptable to various conditions [2].

Overview of Flavor and Fragrance Detection

The world of flavor and fragrance is as increasingly important in food science as it is in consumer preferences. Natural flavors play a key role in shaping how we perceive the taste of beverages and food products. As consumers lean more towards natural and sustainable options, researchers face the challenge of studying these flavors effectively. The process begins when molecules interact with olfactory receptors, triggering a series of neurochemical responses in the brain that contribute to our sense of smell. This intricate relationship between flavor and sensory perception highlights the significance of natural ingredients in our diets [6, 7]. The development of electronic sensors, such as electronic noses and tongues, has further revolutionized flavor assessment. These devices mimic human sensory skills, and therefor identify and distinguish complex odors and tastes. By utilizing selections of chemical sensors, they create unique "fingerprints" for various aromas, enabling the analysis of food quality and authenticity. As these technologies develop, they hold great promise for upgrading our thinking on technological aspects of understanding flavors and fragrances in the food industry [8].

3. MONPs: Characteristics and Properties

3.1. Definition and Types of Metal Oxide Nanoparticles

Nanotechnology typically involves particles that have at least one dimension measuring between 1 and 100 nanometers. In particular, metal oxide nanoparticles are attracting significant interest due to their vast applications in energy, environmental, optical, and biological fields. Nanoparticles have garnered considerable interest due to their various morphological diversities, which include shapes such as hexagonal, nanorod, nano-shell, nanosphere, and nano-cube, among others. Moreover, comparing to bulk materials, metal oxide nanoparticles have unusual immeasurable properties. The optical band gap, higher surface area to volume ratio, and nanoscale dimensions of metal oxide nanoparticles contribute to their unique behaviors and functionalities, paving the way for advancements in technology and materials science. Each type of metal oxide nanoparticle plays a crucial role in addressing environmental challenges, particularly in wastewater treatment and pollution remediation, showcasing the potential of nanotechnology in creating sustainable solutions [9]. MONPs are diverse with various applications in fields such as environmental remediation and catalysis. One prominent type is ZnO_2, which typically measures around 20 nm in size when synthesized without a template and increases to about 28 nm with a template. ZnO is known for its hexagonal structure, making it useful in photocatalytic applications and as an adsorbent for pollutants [10]. Another important metal oxide is Cerium Oxide (CeO_2), which can be produced in sizes ranging from 4 nm to 15–36 nm, depending on the synthesis method used. Its cubic fluorite structure gives it unique properties that are beneficial in various catalytic processes [11]. Copper Oxide (CuO) is also synthesized from various sources, including plant extracts, and is recognized for its antibacterial properties and effectiveness in photocatalytic processes. CuO nanoparticles can be tailored to enhance their efficiency in removing organic contaminants from water [9]. Cobalt Oxide (Co_3O_4) nanoparticles are particularly noteworthy in the field of nanotechnology, typically found in sizes ranging from 10 nanometers to as large as 20–37 nanometers. These nanoparticles exhibit a distinct cubic structure, which contributes to their remarkable properties. Due to their excellent electrochemical characteristics, cobalt oxide nanoparticles are widely utilized in energy storage devices, such as batteries, where they enhance performance and efficiency. Additionally, their catalytic capabilities make them valuable in various chemical reactions, further underscoring their importance in both industrial and environmental applications [12]. Another significant player in the realm of metal oxide nanoparticles is Indium Oxide (In_2O_3). These nanoparticles can be synthesized in sizes starting from around 15 nm when produced without templates, while those synthesized with templates can reach sizes of 20–30 nm. The cubic structure of Indium Oxide nanoparticles allows them to be particularly effective in applications such as transparent conducting oxides, which are essential in electronic devices, as well as in gas sensors that detect various gases in the environment. Their versatility makes them a subject of ongoing research and development in advanced materials science [13]. Tin Oxide (SnO_2) is yet another versatile metal oxide that has garnered attention for its wide range of applications. The sizes of tin oxide nanoparticles can vary significantly, ranging from 6–15 nm to 18 nm, depending on the synthesis method employed. Known for its tetragonal rutile structure, Tin Oxide is extensively used in gas sensors, where its sensitivity to different gases is crucial. Furthermore, it plays a vital role in photocatalytic applications, where it helps in the breakdown of pollutants, showcasing its potential for environmental remediation [14]. Titanium Dioxide (TiO_2) nanoparticles are particularly significant in various scientific and industrial fields. Their sizes typically range from 30–40 nm when synthesized without templates, while those produced with templates can reach up to about 100 nm. Titanium Dioxide exists in two primary phases: anatase and rutile. This dual-phase characteristic enhances its effectiveness in vast ranges of usage and application. Manganese Oxide (Mn_3O_4) nanoparticles are also noteworthy, typically ranging in size from 5 nanometers to 25 nanometers. These nanoparticles are characterized by their tetragonal structure, which contributes to their unique properties. They are primarily used in applications involving batteries, where they enhance energy storage capabilities, as well as in catalysis, particularly in the degradation of organic pollutants. This versatility makes manganese oxide a valuable material in both energy and environmental sectors [15]. Nickel Oxide (NiO) nanoparticles present another interesting case, with sizes varying from 8 nanometers to 31 nanometers, depending on the specific synthesis method chosen and applied. Their hexagonal structure conveys unique electronic properties that are highly chased after in various applications. Nickel oxide nanoparticles are commonly utilized in catalysts and sensors, where their ability to facilitate chemical reactions and detect environmental changes is essential [16]. Lastly, Iron Oxide (Fe_2O_3) nanoparticles are extensively employed across multiple applications, especially in magnetic and photocatalytic processes. Their size and inherent magnetic properties make them particularly ideal for environmental cleanup efforts. For instance, they are effective in removing heavy metals from contaminated water sources, showcasing their potential to contribute to sustainable practices in environmental management [17].

3.2. Synthesis Methods

MONPs can be synthesized through various methods, each offering distinct advantages and applications. These diverse synthesis methods highlight the advancements in the production of metal oxide nanoparticles, each tailored to meet specific needs in applications such as wastewater treatment and environmental remediation. One of the most popular techniques is the template-assisted method (Table 1), which involves using a template to shape and size the nanoparticles precisely. This approach allows for finer control over the morphology and dimensions of the resulting nanostructures, leading to well-defined forms [9, 18].

Table 1. *Summary of matrix-assisted synthesis impact on grain size beside crystal structure of selected metal oxide nanomaterials [9, 19].*

Formed MONPs	Particles Size		Phase/Crystal Structure	
	Without Template	With Template	With Template	Template-Free
ZnO	20 nm	28 nm	Wurtzite	Hexagonal
CeO_2	4 nm (105)	15–36 nm	Cubic fluorite	Face-centered cubic
Co_3O_4	10 nm	20–37 nm	Cubic	Face-centered cubic
In_2O_3	15 nm	20–30 nm	Cubic	Rhombohedral
SnO_2	6–15 nm	18 nm	Tetragonal Rutile	Tetragonal Rutile
TiO_2	30–40 nm	100 nm	Anatase	Rutile
Mn_3O_4	5 nm	25 nm	Tetragonal	Hausmannite Tetragonal
NiO	8 and 26 nm	31 nm	Hexagonal	Face-centered cubic

Another widely utilized method for synthesizing nanoparticles is the sol-gel technique, a process that has drawn noteworthy attention in materials science. This innovative approach involves transitioning a colloidal suspension, commonly referred to as a "sol," into a gel phase. The transformation from sol to gel is a critical step, as it sets the stage for the subsequent processes that lead to the formation of nanoparticles. Once the gel phase is achieved, the next steps involve drying and heat-treating the material. These processes are essential for removing any residual solvents and for promoting the crystallization of the nanoparticles. As a result, the sol-gel method is particularly favored in the scientific community for its ability to produce high-purity nanoparticles. This is crucial because the purity of the nanoparticles directly impacts their performance in various applications. Moreover, one of the stand-out advantages of the sol-gel technique is the incomparable control it offers over the size and morphology of the resulting nanoparticles. Researchers can manipulate various parameters during the synthesis process, such as the concentration of the precursor materials and the temperature conditions, to achieve nanoparticles with specific characteristics tailored to their intended use. A notable example of the effectiveness of the sol-gel method is the synthesis of ZnO nanoparticles. By employing modified sol-gel techniques, scientists can produce ZnO nanoparticles with desired properties, which are useful in a wide range of applications, including electronics, photonics, and even in the field of medicine. The versatility and effectiveness of the sol-gel technique make it a cornerstone in the development of advanced materials and nanotechnology [19]. The hydrothermal or solvothermal method is another prominent technique widely used in the synthesis of metal oxide nanoparticles. This advanced approach involves creating materials under conditions of high temperature and pressure within a solvent, which plays a vital role in the synthesis process. By carefully controlling these parameters, researchers can enable the growth of crystals in a highly controlled manner, leading to the formation of nanoparticles with excellent purity. One of the key advantages of the hydrothermal method is its ability to promote uniform crystal growth. The high-temperature and high-pressure environment enables the solvent to dissolve precursor materials effectively, allowing them to react and form nanoparticles while minimizing impurities. This results in the production of nanoparticles that not only exhibit high purity but also possess well-defined structures, which are essential for their performance in various applications. This technique has been successfully applied to produce a variety of nanoparticles, including titanium dioxide (TiO_2) and iron oxide (Fe_2O_3). The effectiveness of the hydrothermal method in producing these metal oxide nanoparticles showcases its versatility and significance in materials science [9]. Electroless deposition is yet another fascinating approach used in the synthesis of nanoparticles. This technique involves a chemical reduction process that leads to the deposition of metal ions onto a substrate without the need for an external electric field. This unique characteristic sets electroless deposition apart from other methods, making it particularly advantageous in various applications. One of the standout features of electroless deposition is its ability to create highly uniform nanoparticles. The process ensures that metal ions are evenly distributed across the substrate, resulting in nanoparticles that possess consistent size and shape. This uniformity is crucial for many applications, as it directly influences the performance and effectiveness of the nanoparticles in different technologies. A notable example of nanoparticles produced through this method is gold nanoparticles. These tiny particles have garnered significant attention due to their remarkable properties, which make them suitable for a wide range of applications, particularly in surface-enhanced technologies. For instance, gold nanoparticles are widely used in sensors, medical diagnostics, and even in the development of advanced imaging techniques. Their unique optical properties allow for enhanced signals, making them irreplaceable in various scientific and industrial fields [20]. However, microwave synthesis represents a more modern and environmentally-friendly approach to the production of nanoparticles. This innovative method harnesses microwave radiation to accelerate the formation process, making it a standout option in the field of nanotechnology. One of the primary advantages of microwave synthesis is its ability to significantly reduce reaction times compared to traditional methods that could often be really time-consuming. The rapid heating provided by microwave radiation allows for more efficient energy transfer within the reaction mixture. As a result, this technique not only speeds up the overall synthesis process but also offers researchers greater control over the properties of the resulting nanoparticles. This level of control is crucial, as it enables the tailoring of nanoparticles to meet specific requirements for various applications. A remarkable example of the effectiveness of microwave-assisted synthesis is the successful production of TiO_2-MoO_3 nanocomposites. These composites combine titanium dioxide and molybdenum trioxide, resulting in materials that exhibit enhanced properties suitable for a range of applications, including photocatalysis and energy storage. The ability to create such advanced materials quickly and efficiently underscores the growing importance of microwave synthesis in modern nanotechnology [21]. Last but certainly not least, green synthesis methods have emerged as a popular and revolutionary tactic in the field of nanoparticle production. These methods impact biological resources, such as plant extracts and microorganisms, to create nanoparticles in a way that is both environmentally-friendly and sustainable. This shift towards greener techniques not only helps to reduce toxicity associated with traditional chemical synthesis but also simplifies the overall production process. One of the remarkable aspects of green synthesis is its ability to harness the natural properties of plants and microorganisms. For example, copper oxide nanoparticles can be synthesized using extracts from Eucalyptus globulus, a tree known for its medicinal properties. This exemplifies the potential of plant-based methods in producing nanomaterials that are not only effective but also safe for the environment. The use of biological resources in nanoparticle synthesis offers several advantages. It minimizes the need for hazardous chemicals, reduces waste, and often results in nanoparticles that are more biocompatible. This makes green synthesis particularly appealing for applications in medicine, environmental remediation, and other fields where safety and sustainability are paramount. As the demand for eco-friendly solutions continues to grow, green synthesis methods are likely to play an increasingly important role in the development of nanomaterials. By integrating natural resources into the synthesis process, researchers are paving the way for innovative materials that contribute to a healthier planet while meeting the needs of modern technology [22].

4. Electrochemical Sensing Principles

4.1. Fundamentals of Electrochemical Sensors

Electrochemical sensors are specialized devices that detect and analyze specific chemical substances by measuring the electrical signals produced during electrochemical reactions. These sensors typically consist of two key components: a receptor that interacts with the target analyte and a transducer that converts this interaction into an electrical signal. When the analyte binds to the receptor, it triggers a reaction that the transducer can measure, allowing for the determination of the analyte's concentration [23].

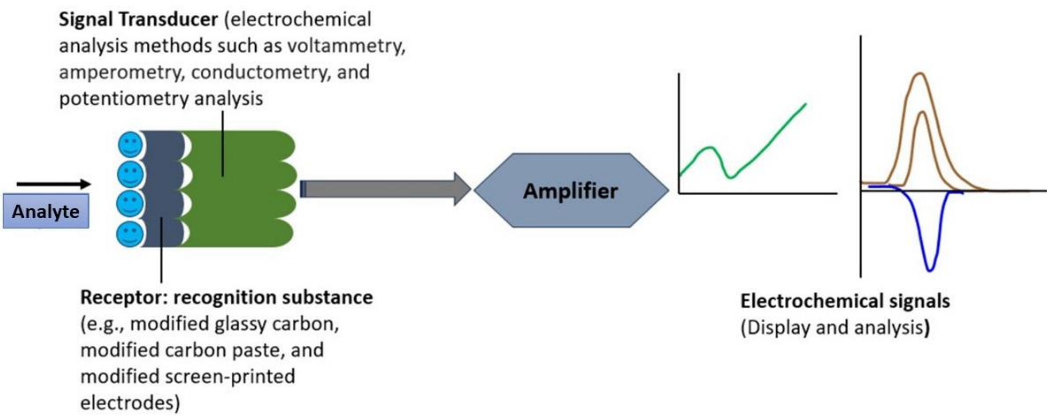

Figure 1. *Schematic illustration of an electrochemical sensor [24].*

Due to the affordability of electrochemical sensors, they have attracted many scientists and engineers in the sensor sector, as this matter makes them a reasonable choice for detecting a wide range of analytes. Their low-cost nature allows for widespread adoption across various fields, including agriculture, food production, oil extraction, environmental monitoring, and biomedical applications. This versatility is a significant advantage, enabling these sensors to meet diverse industrial needs [24, 25]. One of the standout features of electrochemical sensors is their remarkable sensitivity, which allows them to achieve impressively low detection limits. This capability is particularly crucial for applications that require precise and accurate measurements, making these sensors invaluable in various scientific and industrial fields [4]. In addition to their sensitivity, electrochemical sensors are known for their rapid analytical responses. This characteristic makes them ideal for real-time monitoring and alert systems, where timely data is essential. The ability to deliver quick results is especially valuable in situations where immediate action may be crucial [2]. Another remarkable aspect of electrochemical sensors is their versatility in signal reporting. These sensors can generate a variety of signals, such as voltage, current, power output, or electrochemical impedance. This flexibility enhances their applicability across different contexts and industries, allowing researchers and engineers to tailor their use to specific needs and conditions [2]. Moreover, the integration of nanomaterials into electrochemical sensors has proven to be a game changer in this field. The incorporation of these advanced materials significantly enhances the performance of the sensors, improving their sensitivity, selectivity, and overall stability. This enhancement is essential for ensuring reliable measurements, especially in complex environments where interference from other substances may occur. The interaction between nanomaterials and electrochemical sensors represents a significant advancement, paving the way for more effective and dependable sensing technologies [26].

4.2. Types of Electrochemical Sensing Techniques

Electrochemical sensors can be categorized into several distinct types, each characterized by its unique operational principles and specific applications. These classifications are essential for understanding how different sensors function and the contexts in which they are most effective. The various sensing techniques that will be discussed are crucial for the ongoing advancement of electrochemical analysis. Each method brings its own set of advantages, making it particularly well-suited for a range of applications across diverse industries. By tailoring these technologies to meet the specific needs of different sectors, we can enhance the accuracy, efficiency, and reliability of electrochemical measurements, ultimately contributing to significant progress in fields such as environmental monitoring, healthcare, and food safety [2]. First to mention are amperometric sensors set to measure the electric current produced by electrochemical reactions such as oxidation or reduction processes. By applying a voltage between a reference and a working electrode, these sensors can quantify the concentration of an analyte based on the resulting current flow, making them highly sensitive and operative for various chemical analyses. Another method is potentiometric sensors which work by measuring the voltage difference that develops at the interface of the sensor when it interacts with a specific analyte. This occurs under conditions where no current flows, allowing the sensor to establish a local equilibrium. The voltage reading provides valuable information about the concentration of the target substance, making these sensors particularly useful for applications requiring precise concentration measurements [4, 27]. Then there are impedimetric sensors, photoelectrochemical sensors and Electrogenerated chemiluminescence sensors [2]: Impedimetric sensors focus on detecting changes in the impedance of the sensor surface, which can indicate specific interactions between the sensor and the analyte. By applying a small alternating potential and observing how the system responds, these sensors can offer sensitive measurements over extended periods, making them advantageous for monitoring various chemical or biological processes. Photoelectrochemical sensors utilize light to facilitate electrochemical reactions. By combining optical and electrochemical techniques, these sensors can enhance the detection of analytes, providing a powerful tool for applications in fields like environmental monitoring and biomedical diagnostics. Electrogenerated chemiluminescence sensors perform on the principle of measuring light emitted from electrochemical reactions. This technique allows for exceedingly sensitive detection of analytes, as the light signal can be interrelated with the concentration of the target substance, consequently providing a trustworthy method for various analytical applications.

4.3. Role of Nanomaterials in Sensor Performance

Nanomaterials play a crucial role in enhancing the performance of electrochemical sensors, most importantly due to their exceptional sensitivity. This heightened sensitivity is largely credited to their high surface area and unique physicochemical properties, which allow for more operative interactions with target analytes [28]. These sensors are considered to be economical, efficient, and user-friendly, which makes them appropriate for on-site and routine analysis. The unique properties of nanomaterials have meaningfully improved the analytical performance of these sensors. For instance, materials such as graphene derivatives, carbon nanotubes, and metal nanoparticles are commonly used to modify electrodes, enhancing their sensitivity and selectivity [29]. The use of various nanomaterials goes beyond noble metals. Metal oxides such as zinc oxide and titanium dioxide play a key role in enhancing sensor performance. These materials not only boost sensitivity but also improve overall performance metrics of the sensors, including response time and detection limits. Researchers have investigated different manufacture methods, including hydrothermal and microwave-assisted techniques, to develop these nanostructures. These innovative approaches provide better control over the morphology and size of the nanomaterials, ultimately resulting in enhanced sensor functionality [30].

5. Detection of Flavor and Fragrance Compounds

5.1. Common Flavor and Fragrance Compounds

Natural flavors are composed of various compounds, such as acids, alcohols, esters, ketones, and aldehydes, all of which have relatively low molecular weights. Among these, esters are particularly vital as they define the exceptional flavors of fruits, serving as key functional groups responsible for their distinct tastes [31]. Flavor components can vary significantly; they may consist of individual compounds like benzyl acetate or complex mixtures such as vanilla bean extract, depending on their intended use. The food industry has historically utilized synthetic flavor and fragrance substances, with distinguished examples including vanillin, discovered in 1874, and coumarin, identified in 1868. In the realm of flavor chemistry, hydrocarbons play a role, with certain compounds like (E, E)-1,3,5-undecatriene from pineapple revealing a range of aromas, including oily, waxy, fruity, and peppery notes. Essential oils are primarily composed of terpenes, which contribute significantly to flavor profiles. For instance, citral from lemongrass provides a fresh lemon scent, while 1, 8-cineole from eucalyptus offers a camphoraceous aroma. Common alcohols used in flavoring contain n-amyl alcohol and n-heptanol, both of which enhance various food flavors. Aldehydes are also significant in flavor profiles, with compounds like trans-2-hexenal, known as leaf aldehyde, and benzaldehyde, often found in cherry flavors, being particularly remarkable. In terms of esters, a variety of them are widely employed in flavoring, with ethyl butyrate and 2-methylbutyrate being well-known examples recognized for their delightful fruity scents [6]. Moreover, about ketones, specific odd-numbered methyl ketones, such as C7, C9, and C11, are recognized for their unique nutty flavors, which are particularly useful in cheese flavoring [32].

5.2. Importance and Challenges in Accurate Detection

Flavors and fragrances are crucial in the food processing industry. They not only enhance the appeal of food products but also serve a practical purpose: masking unpleasant odors that some foods may have. By incorporating these sensory elements, manufacturers can significantly improve the overall quality of their products, making them more pleasing to consumers [6]. Flavors are not just simple additives; they comprise a complex mix of various compounds, each contributing uniquely to the overall sensory experience. This complexity makes the search for new flavor compounds a vital area of research for both academia and industry. Understanding the types and quantities of these compounds is crucial for creating appealing products that resonate with consumers. Moreover, the distinctive aromas of fruits and vegetables are determined by the specific composition and concentration of their volatile compounds. This means that the unique qualities of different flavors can greatly influence consumer preferences and choices. A well-crafted flavor profile can make a product stand out in a packed market [33]. The growing consumer demand for natural and sustainable products has made it increasingly essential for the food and beverage sectors to focus on natural flavors since they exceedingly play a fundamental role in shaping how consumers perceive and enjoy their food and drinks. As people become more health-conscious and environmentally aware, the significance of flavors and fragrances in influencing their choices cannot be overstated [33]. More importantly, in today's market, consumers are more and more focused on the sensory quality of food, driven by both personal preferences and economic factors. Since the introduction of gas chromatography in the 1950s, scientists have applied this technology to analyze food components efficiently. Remarkably, the human olfactory system has played a vital role in this process, serving as an informal tool for detecting and identifying various flavors and aromas. Therefore, numerous sensory evaluation techniques are employed to assess and refine flavor attributes in food and beverages. These methods are essential for understanding consumer perceptions and preferences, reinforcing the idea that flavors are a crucial factor in creating successful products in the food and beverage industry.

6. Application of MONPs in Electrochemical Sensors

6.1. Case Studies and Recent Advances

A previously done study [34] explores the creation of a new type of electrochemical sensor using copper-based metal-organic frameworks combined with other metal oxides, specifically copper oxide and nickel oxide. The main goal of this research is to develop a reliable method for detecting catechol, a compound found in various natural sources, including tea. Catechol is important to monitor because it can be toxic at high levels, making it essential to have sensitive detection techniques. To create the sensor, the researchers first synthesized copper metal-organic frameworks and then transformed them into copper oxide through a process called thermolysis. They employed a straightforward technique known as hydrothermal synthesis to combine copper metal-organic frameworks with copper oxide and nickel oxide, resulting in nanohybrids. To ensure the quality and characteristics of these materials, the team used several advanced techniques for analysis. These included scanning electron microscopy and transmission electron microscopy to observe the structure, as well as X-ray diffraction and Fourier transform infrared spectroscopy to analyze their chemical properties. The electrochemical performance of the sensor was tested using cyclic voltammetry and differential pulse voltammetry, which helped measure how well the sensor could detect the oxidation of catechol. The results were promising. The modified glassy carbon electrode, which incorporated the copper metal-organic framework/copper oxide/nickel oxide nanocomposite, showed exceptional electrochemical properties. It achieved a remarkably low limit of detection of just 0.0078 micromolar, indicating that it can detect very small amounts of catechol effectively. This sensor also demonstrated high selectivity and reliability when applied to real tea samples, including both black and green teas. The findings of this study highlight the potential of using metal oxide nanoparticles to significantly enhance the sensitivity and effectiveness of electrochemical sensors, especially for detecting important flavor and fragrance compounds. Another study explores the creation of a novel electrochemical sensor designed specifically for detecting vanillin, a vital flavor compound present in vanilla. The sensor is built on a glassy carbon electrode modified with fluorine-doped reduced graphene oxide and enhanced with gold nanoparticles. The researchers highlight the significance of developing simple and cost-effective methods for accurately measuring vanillin, especially given its widespread use in the food and beverage industries. To fabricate the sensor, the researchers followed a multi-step process. They began by synthesizing fluorine-doped graphene oxide using an improved version of the Hummers' method. This material was then applied to a polished glassy carbon electrode, which was subsequently subjected to electrochemical reduction to produce reduced graphene oxide. Following this, gold nanoparticles were deposited onto the surface of the reduced graphene oxide to create the final sensor. The team employed various electrochemical techniques, such as cyclic voltammetry and differential pulse voltammetry, to assess the performance of the sensor in detecting vanillin. These experiments were conducted in a phosphate-buffered saline solution, providing a controlled environment for accurate measurements. The findings indicated that the sensor made with fluorine-doped reduced graphene oxide and gold nanoparticles displayed remarkable sensitivity and selectivity for detecting vanillin. The electrochemical tests revealed well-defined redox peaks, which suggest that the sensor facilitates efficient electron transfer. Impressively, the current measured during the oxidation of vanillin at the modified electrode was nearly four times greater than that recorded with an unmodified electrode. This significant enhancement underscores the beneficial effects of combining gold nanoparticles with fluorine-doped graphene oxide. Furthermore, the sensor exhibited excellent stability and reproducibility, making it a promising tool for practical applications in the detection of flavor compounds [35]. In another recent study [36], the researchers present a novel electronic nose system, referred to as TOMATO-NOSE, designed to detect volatile organic compounds emitted by tomatoes to assess their ripeness and health status. Since the TOMATO-NOSE employs an array of electrochemical sensors to analyze volatile organic compounds released by tomatoes at different ripeness stages, it becomes crucial for determining the optimal harvesting time, as the aromatic profile is indicative of the fruit's quality. This system participates various electrochemical sensors alongside metal oxide semiconductor sensors, enabling effective identification of aroma compounds that contribute to the flavor profile of tomatoes. The data collected from the sensors undergoes Principal Component Analysis (PCA), a statistical method that reduces the complexity of the data while highlighting the differences in aroma profiles between healthy and infected tomatoes. This analysis helps in visualizing the distinct aromatic characteristics associated with various ripeness stages and health conditions. The electrochemical sensors communicate with a smartphone application, enabling farmers to receive real-time data on the ripeness and health status of their crops. This user-friendly interface allows for easy monitoring and decision-making in the field. The TOMATO-NOSE system exemplifies the effective use of electrochemical sensors in agricultural applications, particularly for monitoring flavor and aroma compounds in tomatoes. By providing accurate and timely information about fruit ripeness and disease presence, this technology enhances agricultural practices and supports sustainable farming efforts.

6.2. Comparison with Other Sensing Methods

Metal-oxide sensors offer several advantages over traditional analytical techniques, making them a popular choice for gas detection. One of the primary benefits is their cost-effectiveness. Unlike methods such as gas chromatography (GC) and high-performance liquid chromatography (HPLC), which require expensive equipment and extensive sample preparation, metal-oxide sensors are relatively inexpensive to produce and operate and this makes them accessible for various applications [37]. Additionally, metal-oxide sensors are known for their simplicity and ease of use. They can provide immediate data without the necessity for complex setups or lengthy analysis times. In contrast, traditional methods often involve intricate procedures that can delay results which can make them less suitable for situations requiring immediate feedback [38]. Another exciting advantage to highlight is the miniaturization of metal-oxide sensors, which has been made possible thanks to incredible advancements in micro electro-mechanical system (MEMS) technology. This development means we can now create portable and compact devices that can be used in a variety of settings In contrast, traditional methods often rely on larger, bulkier equipment that takes up a lot of space and isn't easy to move around. These older systems typically require a fixed setup, which can limit their usability in fast-paced or changing environments. By shifting to smaller, more agile sensor technologies, we not only make it easier to conduct tests but also open the door to real-time monitoring and quicker diagnoses. Overall, the miniaturization of metal-oxide sensors is a game changer, allowing for innovative solutions that can better meet the diverse needs of various industries and applications [39]. It's also important to emphasize that metal-oxide sensors are particularly notable for their impressive capability to provide rapid response times. This characteristic is essential in many applications where quick decision-making is necessary. In contrast, traditional detection methods, while often achieving high levels of sensitivity and specificity, frequently do so at the cost of speed. This can be a significant drawback, especially in urgent situations where every second counts [40].

7. Conclusions

As previously mentioned in this review, the use of MONPs in electrochemical sensors is truly transforming how we detect flavors and fragrances. These miniature powerhouses, like ZnO_2 and TiO_2, bring remarkable sensitivity and selectivity to the table, making them invaluable for ensuring food quality. The various synthesis methods explored, from traditional techniques to greener approaches, highlight the creativity and innovation driving this field forward. Plus, with advanced electrochemical techniques like amperometric and potentiometric sensing, we're seeing real-time monitoring capabilities that can significantly enhance food safety. Studies on recent advancements in applying these nanoparticles showcase exciting possibilities for even better sensor performance. However, there are still hurdles to overcome, particularly in refinement of these sensors to meet the specific needs of the food industry. Overall, the findings from this review highlight the critical role of MONPs in enhancing electrochemical sensors, paving the way for innovative solutions in food safety and quality assurance. Continued research and development in this field are essential for addressing existing challenges and harnessing the full potential of these advanced materials.

8. Future Perspectives and Directions

As the important of flavor and fragrance detection filed continues to draw more attention and evolve, several future perspectives and directions can be acknowledged for enhancing the application of MONPs in electrochemical sensors. Future research should investigate the potential of new nanocomposite materials that combine MONPs with other advanced materials, such as carbon nanomaterials or conductive polymers. These composites could further enhance the performance of electrochemical sensors, improving detection limits and response times while providing greater stability and durability. Since there is a growing demand for multi-functional sensors capable of detecting multiple analytes simultaneously, future research should focus on the design and fabrication of electrochemical sensors that integrate various sensing modalities, such as optical and electrochemical techniques. This approach could provide inclusive analyses of flavor and fragrance profiles, enhancing quality control in the food industry. Future research should also concentrate on developing more efficient and environmentally friendly synthesis methods for MONPs. Techniques that utilize renewable resources, such as plant extracts or waste materials, could reduce environmental impact while maintaining high purity and performance. More to say, exploring novel approaches like microwave-assisted synthesis and bio-inspired methods may lead to the production of nanoparticles with tailored properties. Emphasizing sustainability in the development of electrochemical sensors will be vital. Future research should explore the lifecycle assessment of sensor materials and their environmental impact, promoting the use of sustainable materials and practices in sensor fabrication and disposition. The miniaturization of electrochemical sensors will too, be crucial, for their application in portable and important devices. Future studies should aim to reduce the size of sensors while maintaining or improving their sensitivity and selectivity. This development could lead to the creation of handheld devices for present monitoring of flavor and fragrance compounds in various settings, such as food production and consumer markets. Also, since the combination of machine learning and artificial intelligence into sensor data analysis has been off to a promising direction, by utilizing advanced algorithms, researchers can enhance the interpretation of complex data sets generated by electrochemical sensors. An action that'll improve the accuracy of flavor and fragrance detection. Predictive modeling could also facilitate the identification of new flavor compounds and their optimal detection conditions. The future of MONPs in electrochemical sensors for flavor and fragrance detection holds immense potential. By pursuing these perspectives and directions, researchers can significantly advance the field, meeting the growing demands of the food industry and contributing to improved food safety and quality.

Abbreviations

MONPs	Metal Oxide Nanoparticles
TiO_2	Titanium Dioxide
AlO_2	Aluminum Oxide
ZnO_2	Zinc Oxide
Mn_3O_4	Manganese Oxide
NiO	Nickel Oxide
CuO	Copper Oxide
MEMS	Micro Electro-mechanical System
HPLC	High-performance Liquid Chromatography
PCA	Principal Component Analysis
Fe_2O_3	Iron Oxide
ES	Electrochemical Sensors
GC	Gas Chromatography

Author Contributions

Fatemeh Jalili: Investigation, Conceptualization, Supervision, Methodology, Writing– original draft

Abbas Abedfar: Project administration, Conceptualization, Supervision, Methodology

Sepideh Pourvatandoust: Investigation, Writing– original draft and Writing – review & editing

Fatemeh Abbaszadeh: Writing, Validation, Conceptualization

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Schiopu, A.-G., et al., Tailoring the Synthesis Method of Metal Oxide Nanoparticles for Desired Properties. *Crystals*, 2024. 14(10): p. 899.

[2] Baranwal, J., et al., Electrochemical Sensors and Their Applications: A *Review. Chemosensors*, 2022. 10(9): p. 363.

[3] Zhou, Y. and L. T. Kubota, Trends in Electrochemical Sensing. *ChemElectroChem*, 2020. 7(18): p. 3684-3685.

[4] Meti, M. D., et al., Nanostructured Au-graphene modified electrode for electrosensing of chlorzoxazone and its biomedical applications. *Materials Chemistry and Physics,* 2021. 266: p. 124538.

[5] Thiruppathi, M., N. Thiyagarajan, and J.-a. A. Ho, Applications of metals, metal oxides, and metal sulfides in electrochemical sensing and biosensing. Metal, Metal-Oxides and Metal Sulfides for Batteries, Fuel Cells, Solar Cells, *Photocatalysis and Health Sensors*, 2021: p. 209-244.

[6] K R, R., S. Gopi, and P. Balakrishnan, Introduction to Flavor and Fragrance in Food Processing, in Flavors and Fragrances in Food Processing: Preparation and Characterization Methods. 2022, *American Chemical Society*. p. 1-19.

[7] Calín-Sánchez, Á. and Á. A. Carbonell-Barrachina, Flavor and Aroma Analysis as a Tool for Quality Control of Foods. *Foods*, 2021. 10(2): p. 224.

[8] Rodríguez-Méndez, M. L., et al., Electronic Noses and Tongues in Wine Industry. Front Bioeng Biotechnol, 2016. 4: p. 81.

[9] Chouke, P. B., et al., Bioinspired metal/metal oxide nanoparticles: A road map to potential applications. *Materials Today Advances*, 2022. 16: p. 100314.

[10] Rawal, I., Facial synthesis of hexagonal metal oxide nanoparticles for low temperature ammonia gas sensing applications. *RSC Advances*, 2015. 5(6): p. 4135-4142.

[11] Khan, S. B., et al., Exploration of CeO_2 nanoparticles as a chemi-sensor and photo-catalyst for environmental applications. *Science of the total Environment*, 2011. 409(15): p. 2987-2992.

[12] Khalil, A. T., et al., Physical properties, biological applications and biocompatibility studies on biosynthesized single phase cobalt oxide (Co_3O_4) nanoparticles via Sageretia thea (Osbeck.). *Arabian Journal of Chemistry*, 2020. 13(1): p. 606-619.

[13] Xiao, B., et al., Facile synthesis of In_2O_3 nanoparticles for sensing properties at low detection temperature. Sensors and Actuators B: Chemical, 2016. 235: p. 251-257.

[14] Honarmand, M., M. Golmohammadi, and A. Naeimi, Biosynthesis of tin oxide (SnO_2) nanoparticles using jujube fruit for photocatalytic degradation of organic dyes. *Advanced Powder Technology*, 2019. 30(8): p. 1551-1557.

[15] Xue, Q. and Q. Zhang, Agar hydrogel template synthesis of Mn_3O_4 nanoparticles through an ion diffusion method controlled by ion exchange membrane and electrochemical performance. *Nanomaterials*, 2019. 9(4): p. 503.

[16] Abbasi, B. A., et al., Plant-mediated synthesis of nickel oxide nanoparticles (NiO) via Geranium wallichianum: Characterization and different biological applications. Materials Research Express, 2019. 6(8): p. 0850a7.

[17] Raja, K., et al., Sol–gel synthesis and characterization of α-Fe_2O_3 nanoparticles. *Superlattices and Microstructures*, 2015. 86: p. 306-312.

[18] Liang, H. W., S. Liu, and S. H. Yu, Controlled synthesis of one‐dimensional inorganic nanostructures using pre‐existing one‐dimensional nanostructures as templates. *Advanced Materials*, 2010. 22(35): p. 3925-3937.

[19] Bokov, D., et al., Nanomaterial by sol‐gel method: synthesis and application. *Advances in materials science and engineering*, 2021. 2021(1): p. 5102014.

[20] Tang, J., et al., Seed-mediated electroless deposition of gold nanoparticles for highly uniform and efficient SERS enhancement. *Nanomaterials*, 2019. 9(2): p. 185.

[21] Kubiak, A., et al., Highly crystalline TiO_2-MoO_3 composite materials synthesized via a template-assisted microwave method for electrochemical application. *Crystals*, 2020. 10(6): p. 493.

[22] Alhalili, Z., Green synthesis of copper oxide nanoparticles CuO NPs from Eucalyptus Globoulus leaf extract: Adsorption and design of experiments. *Arabian Journal of Chemistry*, 2022. 15(5): p. 103739.

[23] Fakayode, S. O., et al., Electrochemical Sensors, Biosensors, and Optical Sensors for the Detection of Opioids and Their Analogs: Pharmaceutical, Clinical, and Forensic Applications. *Chemosensors*, 2024. 12(4): p. 58.

[24] Shetti, N. P., et al., Graphene–clay-based hybrid nanostructures for electrochemical sensors and biosensors, in Graphene-based electrochemical sensors for biomolecules. 2019, Elsevier. p. 235-274.

[25] Şenocak, A., et al., Ultrasensitive electrochemical sensor for detection of rutin antioxidant by layered Ti_3AlO. 5CuO. $5C_2$ MAX phase. *Food and Chemical Toxicology*, 2022. 164: p. 113016.

[26] Meng, F., et al., Amplified electrochemical sensor employing Ag NPs functionalized graphene paper electrode for high sensitive analysis of Sudan I. *Food Chemistry*, 2022. 371: p. 131204.

[27] Neiva, E. G., et al., PVP-capped nickel nanoparticles: Synthesis, characterization and utilization as a glycerol electrosensor. Sensors and Actuators B: *Chemical*, 2014. 196: p. 574-581.

[28] Rohilla, D., S. Chaudhary, and A. Umar, An Overview of Advanced Nanomaterials for Sensor Applications. *Engineered Science*, 2021. 16: p. 47-70.

[29] Amali, R. K. A., et al., Significance of nanomaterials in electrochemical sensors for nitrate detection: A review. *Trends in Environmental Analytical Chemistry*, 2021. 31: p. e00135.

[30] Baig, N., I. Kammakakam, and W. Falath, Nanomaterials: a review of synthesis methods, properties, recent progress, and challenges. *Materials Advances*, 2021. 2(6): p. 1821-1871.

[31] Shaaban, H. A., et al., Application of biotechnology to the production of natural flavor and fragrance chemicals. *RESEARCH JOURNAL OF PHARMACEUTICAL BIOLOGICAL AND CHEMICAL SCIENCES*, 2016. 7(6): p. 2670-2717.

[32] Van der Schaft, P., Approaches to production of natural flavours, in Flavour Development, Analysis and Perception in Food and Beverages. 2015, Elsevier. p. 235-248.

[33] Vilela, A., et al., Beverage and Food Fragrance Biotechnology, Novel Applications, Sensory and Sensor Techniques: An Overview. *Foods*, 2019. 8(12): p. 643.

[34] Iftikhar, T., et al., Engineering MOFs derived metal oxide nanohybrids: Towards electrochemical sensing of catechol in tea samples. *Food Chemistry*, 2022. 395: p. 133642.

[35] Manikandan, V. S., et al., Electrochemical Sensing of Vanillin Based on Fluorine-Doped Reduced Graphene Oxide Decorated with Gold Nanoparticles. *Foods*, 2022. 11(10): p. 1448.

[36] Meléndez, F., et al., Design of a Multisensory Device for Tomato Volatile Compound Detection Based on a Mixed Metal Oxide—Electrochemical Sensor Array and Optical Reader. *Micromachines*, 2023. 14(9): p. 1761.

[37] Fazio, E., et al., Metal-Oxide Based Nanomaterials: Synthesis, Characterization and Their Applications in Electrical and Electrochemical Sensors. *Sensors*, 2021. 21(7): p. 2494.

[38] Grilli, M. L., Metal oxides. 2020, MDPI. p. 820.

[39] Dey, A., Semiconductor metal oxide gas sensors: A review. *Materials science and Engineering*: B, 2018. 229: p. 206-217.

[40] Maduraiveeran, G., Bionanomaterial-based electrochemical biosensing platforms for biomedical applications. *Analytical Methods*, 2020. 12(13): p. 1688-1701.

Biography

Abbas Abedfar, Assistant Professor, Department of Food Science and Technology, Faculty of Agricultural Sciences, University of Guilan, Rasht, Iran.

Fatemeh Jalili is a master's student at the University of Guilan. She completed her bachelor's degree in Food Engineering at the University of Guilan in 2024. She is currently pursuing a master's degree with a specialization in Food Technology at the University of Guilan

Sepideh Pourvatandoust is a former master's student at Department of Food Science & Technology, Science & Research Branch, Islamic Azad University, Tehran, Iran.

Fatemeh Abbaszadeh, PhD Food Science and Technology, Department of Food Science and Technology, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran

Research Field

Abbas Abedfar: Bread Technology & Sourdough Technology, Food biotechnology and Molecular biology, Fermentation reaction, Lactic acid bacteria fermentation, Dairy food innovation and development.

Fatemeh Jalili: Food Technology.

Sepideh Pourvatandoust: Food Technology.

Fatemeh Abbaszadeh: Gluten free bread and cake, Pickering emulsion, solid colloidal particle-stabilized emulsions.