IJNRD.ORG ISSN : 2456-4184
INTERNATIONAL JOURNAL OF NOVEL RESEARCH AND DEVELOPMENT (IJNRD) | IJNRD.ORG
An International Open Access, Peer-reviewed, Refereed Journal

Applications of electrochemical sensors in the domain of Food, Biomolecules and Metal detection- Review.

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Abstract:

In recent scientific domain, development of sensors is the inevitable research for rapid sensing and quantification of physical and chemical quantities. Particularly, Electrochemical sensors are used as the most preferable sensing driver for various chemical and biological analytes in different fields like chemistry, biochemical, biology, Enzyme Engineering, Agriculture, Cancer technology and biomedical applications. Generally, all the chemical and biochemical substance has the property to follow oxidation and reduction reaction under standard atmospheric condition. These key reactions play a big role on identification or sensing the analytes and further these electrochemical reactions will be converted to electrical signals in terms of current, voltage and Impedance with the help of Transducers. Moreover, the Electrochemical methods are quite rapid and high sensitivity comparatively than all the sensors. In the last ten years, the incorporation of nanomaterial, nanoparticle and nanocomposites in the sensor development has given a high potential to identify the analytes at very lowest level with high precise. In this review paper, we are delineating the importance of electrochemical sensors adopted with nanotechnology for various applications like sensing of food materials, biomolecule and metal ions respectively.

Keywords: Sensors, Nanoparticles, nanocomposites, Electrochemical, Impedance, Biomedical.

Introduction:

In the area of analytical chemistry, the application of nanotechnology leads an unimaginable scientific application for new findings. Due to its nano size in nature, it has a highly splendid chemical, physical and electrical properties [1]. These properties are the major innovative sources for the development of various types of sensors like optical, Electrochemical, Thermal and Magnetic sensors. Likewise, different types of metal nanoparticles have more catalytic and excellent conductivity properties which helps to quantify the chemical or biological analytes by using Electrochemical sensors which is shown in Fig .1 [2]. The electrochemical sensor system comprised with three electrodes includes working electrode made by conductive material, reference electrode and the counter electrode are calomel or standard hydrogen electrode. Generally, all the electrochemical sensors belong to wide family of chemical sensors[3]. These electrochemical sensors transform the sensing information both quantitatively and qualitatively in to an electrical signals interms of analog or digital signals [4]. The application of nanoparticles enhances the sensitivity, stability and selectivity of the fabricated electrode. The sensing potential electrochemical sensors depends upon several parameters like sensitivity, lowest detection limit, range of dynamicity, selectivity, linearity and stability. Now a days, these electrochemical sensors has been employed for the identification of food additives, biological contaminants and heavy metal concentrations[5].

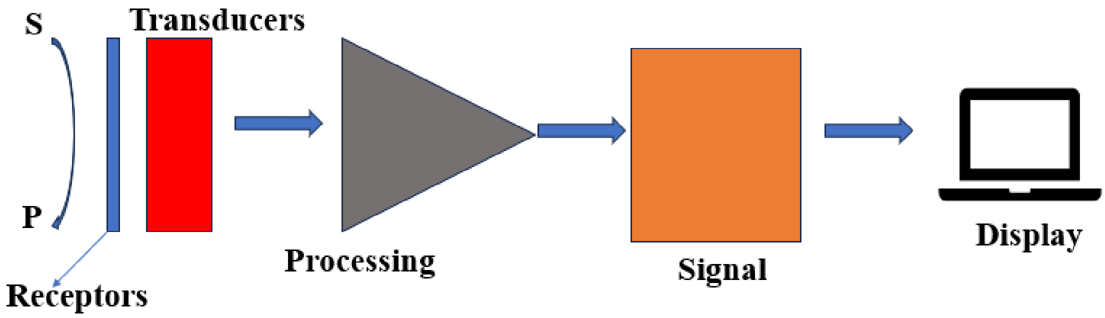

Fig 1. Schematic representation of sensor module [2,6]

According to the technique adopted the electrochemical reaction can create different measurable data in terms of amperometric, potentiometric and impedance ones which helps to understand the resistance capacity in the solution and electrode capacitance [7]. In addition to that, the electrochemical impedance spectroscopy (EIS) elucidates the electron-transfer properties of the modified surfaces for understanding chemical transformations. The EIS studies give an information about the mechanism of sensing ability and rate of sensing for different range of materials such as batteries, fuel cell and corrosion inhibitors [8]. The electrochemical characteristics of working electrode can be signified by comparable circuits embedded with resistance, inductance and capacitance. These equivalent circuit leads to detect analyte concentration and resistance to transfer the charge and double layer capacitance. In the other side, the problem offered with capacitive sensors to detect analyte concentration depends upon the thickness of the sensing layer [9]. In the process of electrochemical sensing process, the analyte concentration measured in terms of current by voltammetry studies which belongs to part of amperometric techniques. Meanwhile there are many methods like cyclic voltammetry, linear sweep voltammetry, differential pulse voltammetry and square wave voltammetry to observe the analyte concentrations in terms of current with respect to voltage [10]. Among all the studies, cyclic voltammetry and sweep wave voltammetry gives a detailed report about the electrochemical characteristics of the fabricated electrode. DPSV and square wave voltammetry explains the redox properties of small electroactive compounds. From these measurements, it is possible to adjust two different process like (i) charging current may be reduced, (ii) only faraday's current only extracted [11].

Nanoparticles and Nanocomposites

Nanoparticles:

Nanoparticles are the tiny particles which has a size in the range of 10 to 100 nm which is an origin component of nanotechnology. The nanoparticles are made up of carbon, metal and its oxide derivatives or organic matter. Based on the dimensions, the nanoparticles can be classified in to Nano dots (fixed point is constant), One dimensional (comprised with one dimension, Eg. Graphene), Two dimensional (which possess two parameters length and breadth, Eg. Carbon nanotubes), Three dimensional (has three dimensions length, breadth and height, Ex: Gold nanoparticles) (Khan I., Khalid S., & Khan I., 2019; Kim K. S., Tiwari J. N. & Tiwari R. N, 2012)[12]: fixed at a single point. The nanoparticles can be formed in different shape: spherical, cylindrical, tubular, conical, hollow core, spiral, flat wire etc, size: nano and structure: amorphous and crystalline, either single crystal solid or multi- crystal solid. In addition to that, the properties of the nanoparticles are heavily influenced by their variations in size and shapes clearly shown Fig 2. Based on the distinct physio chemical properties, the nanoparticles can be successfully applied in various domain like medicinal, environmental, energy dependent research, biochemical sensing, gas sensors etc.,[13]

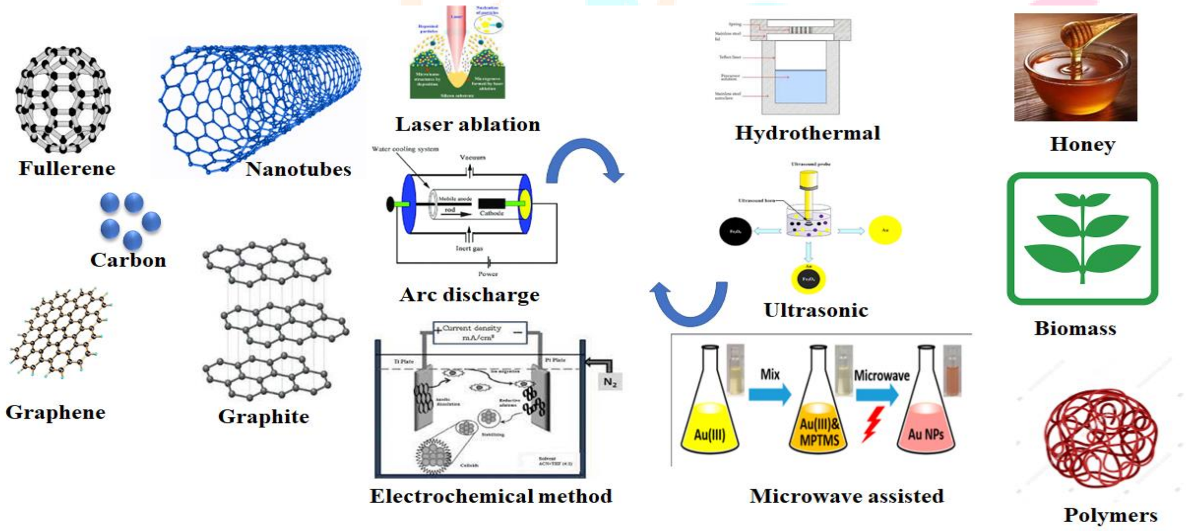

Fig. 2 Various types of nanoparticles and nanocomposites and its synthesis process

Nanocomposites:

Nanocomposites are formed by the combinations of nanoparticles (mineral and metals) and composites which enhances significant composite's properties. It attracts in various research domain due to its unique properties and its capability[14]. Likewise, the addition of nanocomposites can lead to enhance the polymeric properties such as tensile strength, Young's modulus, impact and scratch resistance, electrical and thermal conductivity, thermal and fire resistance [15]. Additionally, the CNT based nanocomposites has wide applications in the domain of electronics, automotive and defence. These properties endeavour the applications nanocomposites along with polymeric components in various domain like heat exchangers, intercoolers on large domain in diesel engines and power plants, alternative for copper alloys, enhance to recover the heat from combustion of flue gas, no chances of corrosive effect on the surface. Recent research stating that, the mixing of CNT with ceramic matrix composites enhances the properties of strength of the materials[16]. Generally, the reinforcements of nanotube enhance the fracture of the materials because of energy absorption through their elastic behaviour during deformation of materials. But, it is very difficult to fabricate with uniform dispersion on surfaces of ceramic composite matrix [17]. Destruction of the nanotubes happens at high temperatures and very high reactive environments with many ceramic products. But the metal matrix composites have well signified physical properties which helps to reduces the weight of the composites [18]. The addition of metal nanoparticles and CNTs improves structural applications and induce the improvement of yield modulus of material than the micro-size reinforcements. Additionally, the homogeneity dispersing of CNTs throughout the matrix improves very high interfacial bond strength between the matrix and structural properties of nanotubes. In this review paper, we are discussing about the application of nanomaterials for sensing various analytes by using electrochemical methods in various domain [19].

Electrochemical sensors for food analysis

More interestingly in the domain of food chemistry and clinical applications, the analysis of natural antioxidants will be playing a big role for various beneficial impacts on human health, reduces the pathological effects in human system and defend from oxidative stress [20,21,22]. Generally, the antioxidants are classified according to their chemical structure and reactivity.

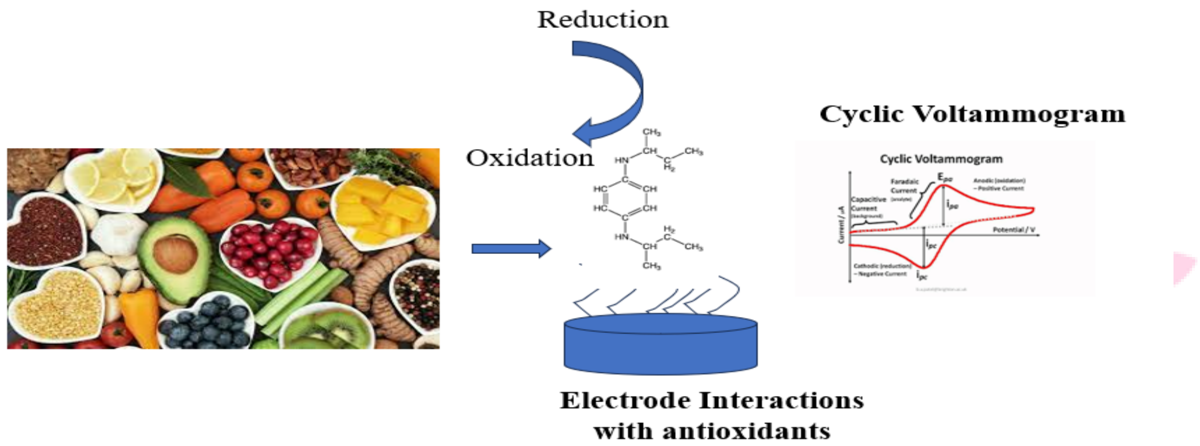

Fig 3. Schematic diagram for the interaction process of Electrochemical sensors with antioxidant products [23, 24]

Nevertheless, the action of antibiotics is firmly followed with redox properties. [25,26,27] stating that, the anti-oxidants observed in the fruits and plants, hydroxycinnamic acids (HAs) are very beneficial bioproduct to enhance the health, technological purpose and for marketing[28].In this part of research, the activity of antioxidants is mainly depending upon the redox process as we discussed earlier. However, the redox property of any reaction can be possibly analysed by electrochemical methods [28]. In the recent studies shows that, most of the antioxidants, phenolic antioxidants and HAs been separated and quantified by the chromatographic method. But those methods require huge amount of solvent for the separation process. But, the electrochemical pay more attention on analysis of antioxidants due to the direct analysis of redox properties with fast, accurate, more sensitive and very importantly low cost schematically represent in Fig 3. (Dicarlo et al.,2014) [29] stating that, the incorporation of gold nanoparticles along with chitosan had shown a higher potential of affinity to carried out the redox reactions with the help of functional groups like hydroxyl and amino groups. In addition to that, (Dicarlo et al.,2014) [30]observed the variation of redox potentials of different antioxidants like catechol's, hydroxycinnamic acids, and flavonoids which is structurally differed was investigated with respect to its chemical structures and oxidation and reduction properties of analytes. Additionally, the electrochemical studies help to interperate the functional groups and steric hindrance effect of the analytes. Curulli and co-workers [31] elucidated the electron transfer properties in the AuNPs–chitosan modified electrodes from the surface functional groups which helps to endeavour the interaction with antioxidants. And also [32] observed a better sensing property for the chemical compounds which has two hydroxyl groups in ortho and meta positions of benzene rings. Moreover, Curulli et al., 2014 delineating that the size and distribution of AuNPs into the polymeric matrix will be affect the interaction of antioxidants. Additionally, the chitosan matrix embedded with colloidal AuNPs produced by green route shows a significant sensing property of the antioxidants by reducing AuII to Au0 in aqueous solutions with respect to its organic acids. Likewise, the changes of chemical properties in the with respect to its nature of the acid shows a significant variation in the reduction rate of silver nanoparticles when it acts as a catalyst. (Filik H et al., 2013)[33] stated that, the AU-chitosan nanocomposites attesting high sensing ability and selectivity on caffeic acid by the Differential pulse stripping voltammetry methods. In addition to that, he observed a linear response of detection was achieved by the sensors is around 5.00×10^{-8} M to 2.00×10^{-3} M, and the LLOD was 2.50×10^{-8} M without any interference of catechin or ascorbic acid. Filik and co-workers [33] also concentrated on development of Nafion doped graphene nanocomposites for the determination of caffeic acid using Nafion-graphene oxide modified glassy electrode was fabricated to examine the oxidation and reduction of caffeic acid. From the obtained result, the first linear segment observed upto 10 μM and the second linear segment was observed at 9.1×10^{-8} M using square wave voltammetry method [34].

Table 1 : Details of electrochemical sensors for the detection of CA by nanomaterials

S.no	Electrochemical methods	Nanocomposites	Detection limit	Reactant	Reference
1.	SWS	Nafion/ER-GO/GCE	10^{-7}–1.0×10^{-6}	White wines	[35]
2.	DPV	MIS/AuE	5.00×10^{-7}–6.00×10^{-5}	White wines	[36]
3.	DPV	RGO@PDA/GCE	5.0×10^{-9}–4.55×10^{-4}	Wines	[37]
4.	DPV	Au–PEDOT/rGO/GCE	1.00×10^{-8}–4.60×10^{-5}	Red wines	[38]
5.	DPV	PdAu/PEDOT/rGO/GCE	1.90×10^{-9}–5.50×10^{-5}	Red wines	[39]
6.	Amperometry	SrV_2O_6/GCE	1.00×10^{-8}–2.07×10^{-4}	No real samples	[40,41]
7.	DPV	Au/PdNPs/GRF/GCE	3.00×10^{-8}–9.40×10^{-4}	Fortified wines	[42]

Electrochemical sensors for quantifying biomolecules

The quantification of Dalton level biomolecules like nucleic acids, enzymes and proteins is majorly carried out by biological and physiological functions through transferring genetic evidence, based on biological activity, initiating catalytic activity in cellular levels [44]. There are various conventional methods namely electrophoresis, western blot, polymerase chain reactions process has bee followed to analyse the biomolecules by qualitatively as well as quantitatively. But these processes take more time taking process and quite slower process. Recently, there are various research work confirming that the electrochemical method of analysis is helpful to find out these biomolecules very rapid and easy. In addition to that, the analysis of redox reactions in the electrochemical methods leads to observe and diagnose the infection of viral diseases in early stage [45,46,47,48,49].

Table 2: Electrochemical sensing methods to quantify biomolecules

S.no	Electrode	Nanomaterial	Biomolecules	Electrochemical methods	Reference
1.	Screen-printed electrode	Au nanoparticles/TFO probe/Methylene Blue/Target DNA	DNA	CV/SWV	[50]
2.	Au electrode	Thiol-group/aptamer/tetra-ferrocene	Thrombin	DPV/EIS	[51]
3.	ZnO nanoparticle electrode	Gold-coated glass/ZnO-NP/APTES/Glutaraldehyde/MMP-9 Antibody	MMP-9	CV/EIS	[52]
4.	Au electrode	Split aptamer 1/E2/Split aptamer 2	Estrogen (17-β Estradiol)	CV/DPV	[53]
5.	Screen-printed carbon electrode	Carbon-nanotube/Antibody1/hCG/Au-Antibody 2	Human chorionic gonadotrophin (hCG)	CV/DPV	[54]
6.	Au electrode	Selenium/peptide/ Na_2MoO_4/ssDNA		MMP-2	[55]

Recently, the researchers have been developed Geno sensing technology for the quantification of DNA which has more sensing methods, inexpensive and rapid performance than the basic conventional methods. This technology has been applied in various disciplines like disease diagnosis, forensic applications and screening of drugs [56,57]. [58] depicted that, the self-signal of DNA has been detected through the modified carbon paste electrode by hybridised ssDNA, tungsten sulphide and indole-6-carboxylic acid. The electrode has the capability to detect the ssDNA molecule in pM/L by using cyclic voltammetry and EIS method. [59] observed that, the metal polymeric composite electrode Pt||MoS_2-polyaniline has the ability to detect the DNA concentration in the aqueous solution by Differential stripping voltammetry and CV method of around 10^{-15} M without any labelling and amplification process. Another biomolecule, Enzymes, are the important biomolecule which plays an important role on degradation, absorption, oxidation and reduction process. During the process, the enzymes found in every part of the organ in the body. In recent research studies stating that, the scientific community develops different types of platforms that uses to identify the specific enzymes which acts like a biomarker without causes any damage. Normally, the enzyme activity and its catalytic activity can be elucidated by electrical signals which is depicted in Fig 4. In the process of glucose sensor, the amount of glucose present in the blood stream can be indirectly measured by ferrocene and potassium ferricyanide which acts like a mediator for the oxidation process in the glucose sensors.

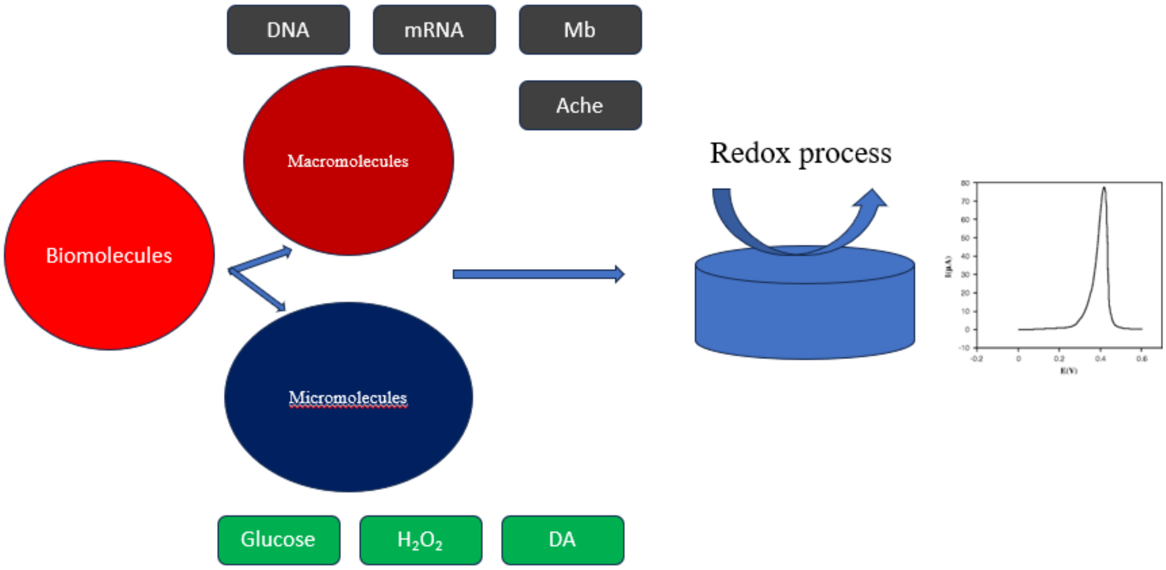

Fig 4. Schematic diagram for the interaction process of micro and macro-biomolecules with Electrochemical sensors [54]

Thrombin is another important enzyme which can be easily and successfully detected by fibre optics and infrared fluorescence sensors. But these detection methods take more time and the precise level is very less. [58] depicted the sensing of thrombin concentration around 1.8nM by the electrochemical sensor made up of tetra-ferrocene at the 3′ terminal and a sulphur group at the 5′ terminal. Additionally, [59] developed a platform fabricated by two aptamers which can be acts as a sensing unit as well as electroactive indicator in the detection of thrombin. In another side, the addition carbon-based graphene enhances the transfer of electrons and amplifies the oxidation and reduction signals which reaches the detection limit of around 0.03pM. Recently, the researchers are more concentrating on development of another important enzyme matrix metalloproteinase, a zinc complexed protein which has the properties of invasion of tumour, acting as a biomarker identifying infection, inflammation and growth of cancer cells. [60] elucidated that the gold-based biosensor labelled with methylene blue platform has the capability to diagnose the cancer cells through electrochemical process. In 2020, [61] attested the detection of MMP-9 could be possible by zinc oxide nanoparticles using electrochemical method. In addition to that, the modification of gold substrate by zinc oxide nanoparticles can be able to detect cyclic voltammetry process. Likewise, the entrapment of APTES along with glutaraldehyde and ethanolamine enhances the sensitivity and selectivity on detection of MMP-9 through antibody conjugation. In case of detection of hormones, [57]fabricated screen-printed electrode by the combination of carbon and , 1-pyrenebutyric acid-N-hydroxy-succinimide ester (PANHS), and anti-hCG antibodies leads to detect the concentrations of hCG by cyclic voltammetry method at the scan rate of 10 to 100 mV/s. Also, the micro electrode shows higher potential than the macro electrode for the detection of hormones in the range of (1pg/mL).

Electrochemical sensors for the detection of heavy metals in the aqueous solutions

Heavy metals are the toxic heavy which has the tendency in highly soluble nature in aqueous medium and soil. The major sources of heavy metals are majorly from the different anthropic activities like mining, smelting, galvanising processes [62]. But some metals like iron, cobalt, copper, zinc are the essential metal ions for the human being with some permissible limitations. At the same time, the metals namely lead, chromium, Arsenic, Mercury are the major toxic heavy metals which causes several health issues for all the creatures living in the nature [63]. There are various analytical methods like UV Spectrophotometer, Atomic absorption spectroscopy and Inductive couple plasma spectroscopy has been traditionally used for the measurement of heavy metal in the ppm to ppb levels. But these methods take more time, utilization of huge chemicals, more man power is required [64]. Therefore, in those situations, these traditional methods can be replaced by electrochemical methods. In the electrochemical methods, the cationic heavy metals and anionic on metals can be quantified by electrochemical methods based on the oxidation and reduction potentials which has elucidated in Fig 5 [65].

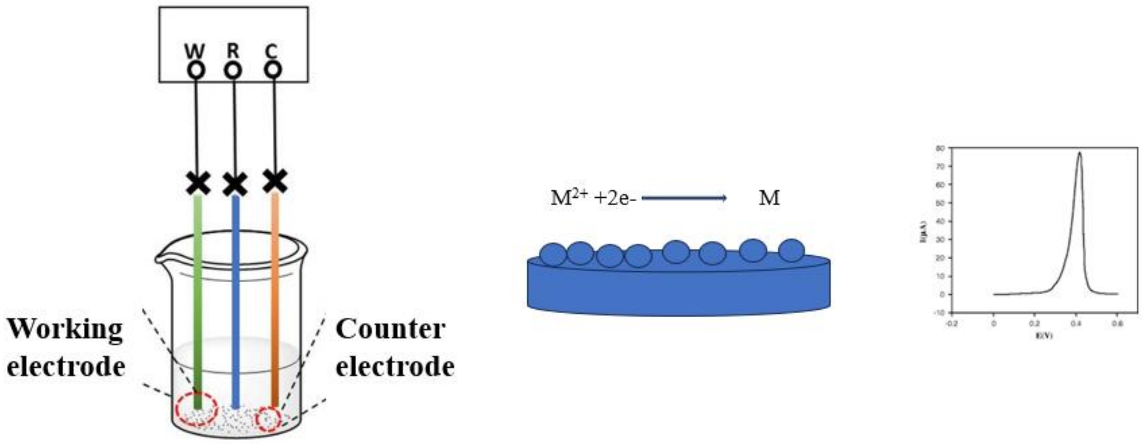

Fig 5. Schematic representation of electrochemical setup for the detection of metal Ions [65]

But the hanging drop mercury electrode has more drawbacks on the detections silver, mercury and gold and also now it is clearly stopped due to its higher toxic effect. Likewise, Kirowa-Eisner et al. attested the detection of cadmium, lead and copper by using gold and silver coated electrode. But the researcher observed that, the gold coated electrode is not the preferable one for sensing the lead and cadmium on same time due to the overlapping of stripping peaks[66]. In spite of that, the silver electrode has shown a higher potential on the detection of cadmium and lead with high repeatability and stability without following any pretreatment process. Another scientific group called Compton's developed gold and silver electrode for the detection of Arsenic(III) with LLOD of around 1ppb in aqueous solutions carried out by the anodic stripping voltammetry assisted by Ultrasound waves. Similarly,[67] achieved the detection of lead in the range of 0.28ppb using crystalline form of gold electrode. [68] developed copper electrode for the detection of pico level of concentrations of Arsenic(III) present in tap water followed by differential pulse stripping voltammetry [69]. [70], depicted that the sensing of chromium (VI) by gold electrodes by cyclic voltammetry with lower level of detection of 0.228 ppm. In addition to that, the addition of carbon composite electrode showed higher sensing ability of chromium(VI) of around 4.4 ppb. During 2000, researchers introduced bismuth field electrodes for the separation of intermetallic compounds like cadmium and lead which is alternative to mercury film electrode. [71] used bismuth film electrode as a substrate coated on the glassy carbon surface and screen-printed carbon ink for the detection of Cd^{2+} and Pb^{2+}. [72] observed that the electroplating of Bismuth on electrode surface shows a poor performance. Then they found three different methods such as ex-situ plating, In-situ plating and confining on bismuth on electrode surface. The ex-situ plating of Bismuth on electrode surface was carried out at -0.5 and -1.2V at a deposition time of around 1-8 min. But in the in-situ process, the bismuth ions added directly in the sample solution for coating on electrode surface. In the last method, the Bismuth ions coated on electrode surface as oxide form. Note: In all the process, the solution should be maintained under acidic conditions. Recently, EIS(Electrochemical impedance spectroscopy) and alternating current voltammetry methods selectively used to determine the concentration of analytes in aqueous solutions [73]. [74] developed a rapid separation tool for detecting lead concentrations in blood samples. In this process, the impedance has been analysed modulated FET sensor based on ion selective membrane as a portable sensor measurement unit for the detection of lead which could be able to found 10^{-15} µM with in 15mins.

Conclusion:

In this review paper we majorly concern on discussion about electrochemical methods for sensing different types of domains like food domain, sensing of biomolecules and metal detecting sensors using cyclic voltammetry, Differential anodic stripping voltammetry and EIS methods. In addition to this article given a summary look on impact of sensing by the addition of nanomaterials on electrodes was discussed till recent times of research. In this review articles, the performance of electrochemical sensors, sensitivity, stability was discussed three major domains. In addition to that, the resistance offered by the solution and the electrode was discussed in in several processes. From the review, we concluding that, the electrochemical sensors could be used in domain for detecting the analytes very rapidly with high sensitivity on both higher and lower concentrations of analytes.

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