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ORIGINAL ARTICLE

Thermal Influence on the Activation Energy of Nano Antibiotics (Erythromycin, Tetracycline, Levofloxacin, Ciprofloxacin, and Gentamicin) in Blood Matrices Utilizing Cyclic Voltammetry

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ABSTRACT

The development of Nano-antibiotics, which provide enhanced bioavailability and selective administration, has completely altered how infectious diseases are treated. However, their effectiveness might be changed by the physiological environment, primarily changes in temperature. This study uses both theoretical assessment and data from experiments to investigate how elevated temperatures impact the activation energy of Nano-antibiotics in a blood media. The data show that higher temperatures reduce activation energy, possibly enhancing antibiotic efficacy but simultaneously heightening concerns concern stability and adverse effects. This current research examines the effect of increased temperatures on the activation energy and stability of Nano-formulated antibiotics—erythromycin, tetracycline, levofloxacin, ciprofloxacin, and gentamicin—in a medium of blood. Optimizing therapeutic efficacy requires knowledge of these outcomes, particularly in cases of fever or during hyperthermia therapies. Temperature is a key factor influencing the pharmacokinetics and activity of antibiotics, particularly when administered as nanoparticles in physiological settings such as blood. This study examines the impact of elevated temperatures on the activation energy of Nano-antibiotic variants of erythromycin (ERY NPs), tetracycline (TET NPs), levofloxacin (LEV NPs), ciprofloxacin (CPR NPs), and gentamicin (GEM NPs) in a blood media .Employing Arrhenius kinetics, we analyzed activation energies at standard and raised temperatures, discovering that higher temperatures often reduce activation energy and enhance reaction speeds. Employing Arrhenius kinetics, we analyzed activation energies at standard and raised temperatures, discovering that higher temperatures often reduce activation energy and enhance acceleration the reaction. There is discussion of the implications for safety and efficacy of therapy.

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1- INTRODUCTION

A key component of drug kinetics and dynamics is related to how antibiotics interact with biological systems. However, by altering molecular mobility, diffusion velocity, and overall reaction kinetics within biological matrices like blood, modification in temperature can have a significant effect on these interactions. Improving

medication effectiveness, stability, and transport under both physiological and non-physiological situations requires a Comprehension of how high temperatures impact the activation energy of antibiotic interactions especially at the nanoscale level. Nanotechnology has altered antibiotic research by enhancing mobility, bioavailability, and specific absorption utilizing nanoparticle-based formulations [1, 2].The discovery of Nano-formulated antibiotics with enhanced solubility, bioavailability, and targeted distribution has made nanotechnology a game-changer in antimicrobial treatment. Because of their larger surface area and controlled release characteristics, these Nano-antibiotics—which include formulations of erythromycin, tetracycline, levofloxacin, ciprofloxacin, and gentamicin—have demonstrated improved therapeutic efficacy when compared to their traditional counterparts [3, 4].By altering molecular interactions and barriers to energy in biological contexts, nanotechnology modification of antibiotics including erythromycin, tetracycline, levofloxacin, ciprofloxacin, and gentamicin can enhance their efficacy [5] . But there is still a lack of research on these Nano antibiotics' thermal stability and activation energy characteristics at high temperatures. The temperature directly influences the reaction rate constant and kinetics, as stated by the Arrhenius equation; hence, examining these impacts enhances comprehension of drug degradation, reaction processes, and stability during storage or in febrile circumstances [6]. Therefore, maximizing the therapeutic usage of Nano-antibiotics requires knowledge of their temperature-dependent kinetic behavior in blood. Activation energy offers important information on degradation processes and reaction rates and is a crucial metric for describing how sensitive chemical reactions are to temperature changes. However, biological component interference and the requirement for substantial sample preparation make it difficult to determine activation energy accurately in complex biological matrices using traditional analytical methods.

The present study shows the impact of increased temperatures on the activation energy of several Nano antibiotics in the samples of blood to enhance the understanding of their thermodynamic and kinetic properties in medicinal applications. By improving drug transport, stability, and targeting the development of Nano-antibiotic formulations opens up new avenues for treating bacterial infections. However, therapy is further complicated by the interaction of Nano-antibiotics with the physiological milieu, particularly at different temperatures. In order to optimize dosing Forms and minimize side effects, Studying how rising temperatures affects the activation energy of Nano-antibiotics is essential since fever may alter the pharmacokinetics and effectiveness of medications [2, 7, 8]. A potential strategy for improving the availability and effectiveness of antimicrobial medicines is the use of Nano pharmaceuticals as agent. However, temperature changes can have a significant impact on how well they work because they can modify their activation energy and in turn their antibacterial activity.

The current study Demonstrate the kinetic and thermodynamic properties of certain Nano pharmaceuticals at different temperatures. Antibiotic resistance has spurred the development of advanced drug delivery systems, including Nano pharmaceuticals antimicrobial agents at the nanoscale. Their interaction with physiological environments, such as blood, is subject to multiple variables, with temperature being a crucial but often overlooked factor. Understanding the thermodynamic and kinetic behavior of Nano pharmaceuticals at elevated temperatures is essential for improving their therapeutic potential and safety [9, 10]. Antibiotics can accumulate in the human body through food metabolism, potentially impacting human health and safety. Therefore, developing simple and sensitive methods for rapidly assessing antibiotic levels is crucial. In the development of next-generation biosensors, nanomaterials, with their unique thermal, mechanical, optical, and electrical properties, have been identified as some of the most promising materials for unlocking new possibilities. Electrochemical signal conversion mechanisms have been employed in constructing biosensors using various types of nanomaterials, including quantum dots, metal-organic frameworks, magnetic nanoparticles, metallic nanomaterials, and carbon nanomaterials [11]. Electrochemical approaches offer a robust and increasingly favored method for examining kinetics in complex biological settings. Cyclic voltammetry in generated has been researched because of its great sensitivity to redox-active species and its capacity to directly study electron transfer processes, which are intimately related to degradation routes and reaction kinetics .It has been effectively used to monitor biochemical and pharmacological processes in biological samples, such as blood and other physiological matrices, and allows for quick, real-time analysis with little sample preparation [12].

The application of cyclic voltammetry methods for the analysis of physiologically relevant chemicals, such as medicines, metabolites, and oxidative stress indicators, even in complicated media, is further demonstrated by recent developments in electrochemical sensing. In the presence of interfering biomolecules, these techniques ensure sensitivity and selectivity while enabling precise accurate characterization [13]. In addition, cyclic voltammetry is very useful for researching temperature-dependent activation energies since it enables comprehensive insight into the thermodynamic and kinetic aspects of redox processes [14]. This study aims to investigate the effect of temperature on the activation energy and electrochemical behavior of selected Nano antibiotics, including

erythromycin, tetracycline, levofloxacin, ciprofloxacin, and gentamicin, in blood matrices using cyclic voltammetry. The study seeks to evaluate how thermal changes affect the electron transport kinetics and electrochemical responses of these Nano antibiotics within a biological environment. Furthermore, the study aims to determine the activation energy values associated with their electrochemical interactions and assess the suitability of cyclic voltammetry as a reliable analytical technique for investigating the thermal stability and kinetic properties of antibiotic nanostructures in complex biological systems.

2- MATERIALS AND METHOD

Erythromycin, tetracycline, levofloxacin, ciprofloxacin, and gentamicin powder from Hyper Chem (China), NaOH and HCl from Fluka Company (Germany), ascorbic acid from SER (China), All preparation solutions were made using double-deionized water employing a normal blood sample from the Center Medical City in Baghdad.

2.1 Synthesis of Nano Biotic Compounds

The Lyophilization method was used to convert each of the micro erythromycin tetracycline, levofloxacin, ciprofloxacin, and gentamicin to nanoparticles (NPs) using the lyophilizer [15]. Shown in Fig 1 microscopic methods, Atomic force microscopy (AFM) and field emission scanning electron microscopy (FESEM) were used to describe the conversion of micro antibiotic to NPs. The results of FESEM analysis elucidating the morphology and dimension of all the nanobiotic were calculated. All the nanobiotic were synthesized using a precipitation method. The micro antibiotic was dissolved in a suitable solvent, and a stabilizing agent was added to form the nanoparticles. The mixture was subjected to centrifugation and washing to remove excess solvents and stabilizers. The size, morphology, and structural properties of the nanoparticles were confirmed using Field Emission Scanning Electron Microscopy (FESEM), Atomic Force Microscopy (AFM), X-ray diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), and ultraviolet spectroscopy (UV).

2.2 Blood Medium Preparation

A simulated blood medium was prepared by mixing a blood sample with deionized water (DW) in ratio of (1 ml blood: 10 ml DW). The pH of the medium was adjusted to 7.4 for normal conditions, and additional experiments were conducted at acidic (pH 5.5) and basic (pH 9.0) conditions to assess the impact of pH on nanoparticle behavior.

2.3 Preparation of Nano Antibiotic Compounds

The Lyophilization technique was used to convert the micro antibiotic substance into nanoparticles utilizing the lyophilizer device from LABCONCO Company (America).

2.4 Microscopic and Spectroscopic Characterization of Nano Anti biotic Compounds

Different microscopic methods used to characterize erythromycin (ERY NPs), tetracycline (TET NPs), levofloxacin (LEV NPs), ciprofloxacin (CPR NPs), and gentamicin (GEM NPs), such as field emission scanning electron microscopy (FESEM), atomic force microscopy (AFM), were employed to characterize the ERY NPs. Also, spectroscopic analysis was studied to characterize the structure of ERY NPs such as Fourier transforms infrared (FTIR), Ultraviolet–visible (UV-Visible), and X-ray diffraction (XRD) to prove the nano compound.

2.4.1 Field Emission Scanning Electron Microscopy (FESEM)

Field Emission Scanning Electron Microscopy (FESEM) is a viable imaging method for examining the shape and size of nanoparticles erythromycin (ERY NPs), tetracycline (TET NPs), levofloxacin (LEV NPs), ciprofloxacin (CPR NPs), and gentamicin (GEM NPs), Fig. 2 describe the shape and surface characteristics of the nanoparticles. Common shapes have rod-like forms with 46, 29.8, 122, 92, and 90.55 nm dimensions of the nanoparticles respectively.

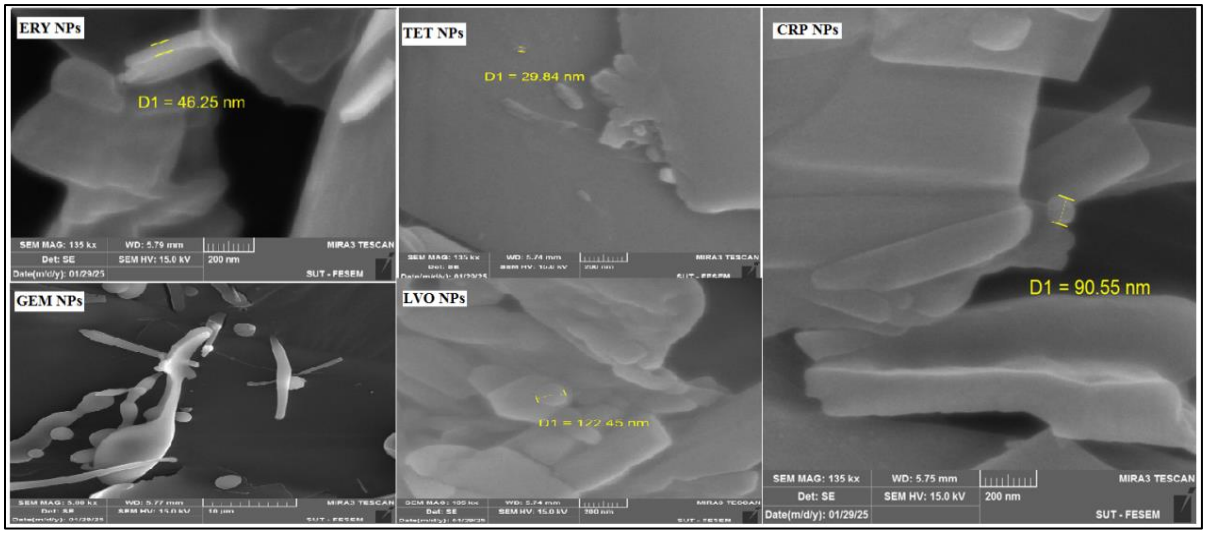

Fig (1): FESEM of Nano antibiotic compounds

2.4.2 Atomic Force Microscopy (AFM)

Atomic Force Microscopy (AFM) is a valuable technique for analyzing the surface characteristics of nanoparticles, including erythromycin (ERY NPs), tetracycline (TET NPs), levofloxacin (LEV NPs), ciprofloxacin (CPR NPs), and gentamicin (GEM NPs). AFM provides detailed topographical maps of the nanoparticle surface. Fig. 3 describes the roughness, texture, and any features observed.

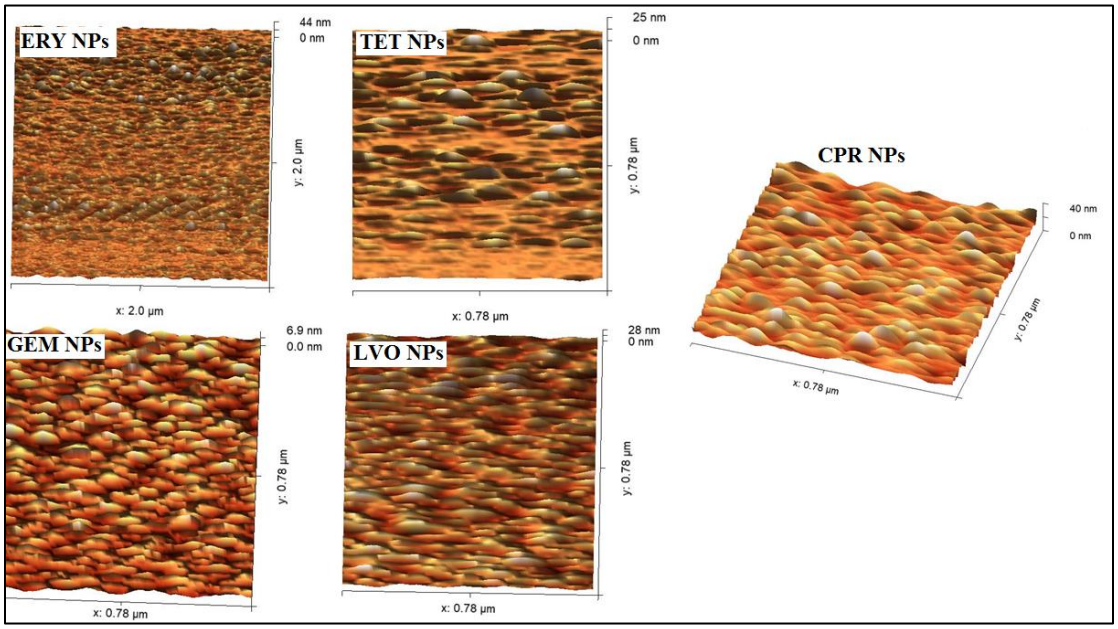

Fig (2): AFM of Nano antibiotic compounds

2.4.3 Fourier Transform Infrared Spectroscopy (FTIR) Study

Fourier transform infrared (FTIR) spectroscopy study used to confirm that erythromycin is present in the nanoparticle formulation. The sample (erythromycin (ERY NPs), tetracycline (TET NPs), levofloxacin (LEV NPs), ciprofloxacin (CPR NPs), and gentamicin (GEM NPs) are scanned from 4000 to 400 cm^{-1}.as shown in Fig.4.

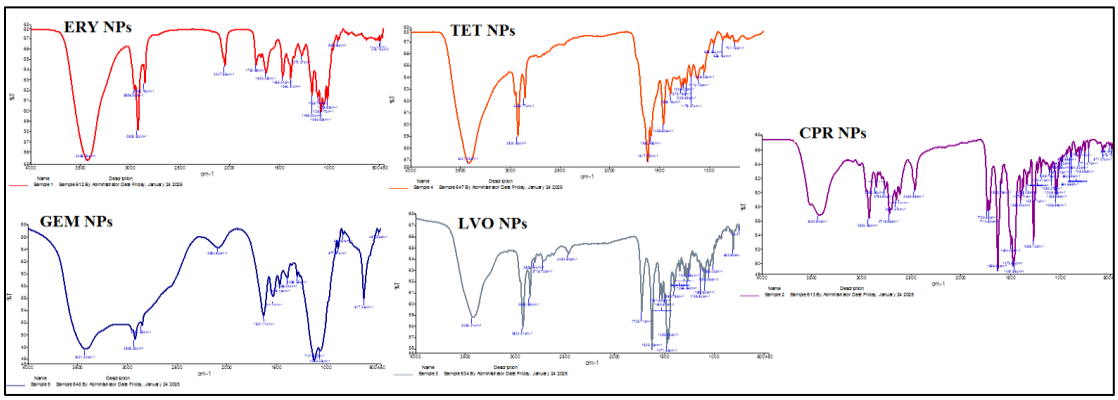

Fig (3): FTIR spectroscopy of Nano antibiotic compounds

2.4.4 UV-Visible Spectroscopy

Erythromycin (ERY NPs), tetracycline (TET NPs), levofloxacin (LEV NPs), ciprofloxacin (CPR NPs), and gentamicin (GEM NPs) aren't particularly flashy in the UV-Vis region. It doesn't have big conjugated systems or aromatic rings strutting down the runway at 300 nm. But it does absorb weakly in the UV region (around 200–230 nm) as shown in Fig.5.

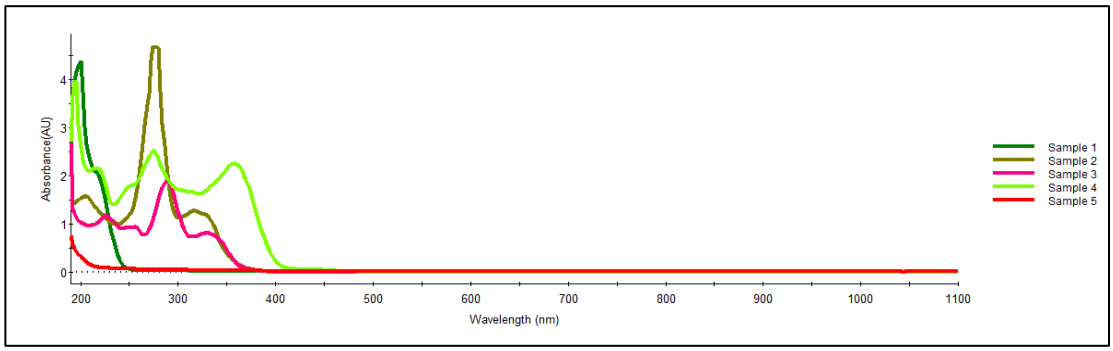

Fig (4): UV-Visible spectroscopy of Nano antibiotic compounds

2.4.5 XRD Spectroscopy

X-Ray Diffraction (XRD) Spectroscopy of erythromycin (ERY NPs), tetracycline (TET NPs), levofloxacin (LEV NPs), ciprofloxacin (CPR NPs), and gentamicin (GEM NPs) where things get really judgmental. This technique doesn't just look at the sample, it scrutinizes its soul. XRD is used to determine the crystalline structure of materials, and in the context of all Nano antibiotic compounds illustrated with Fig.5.

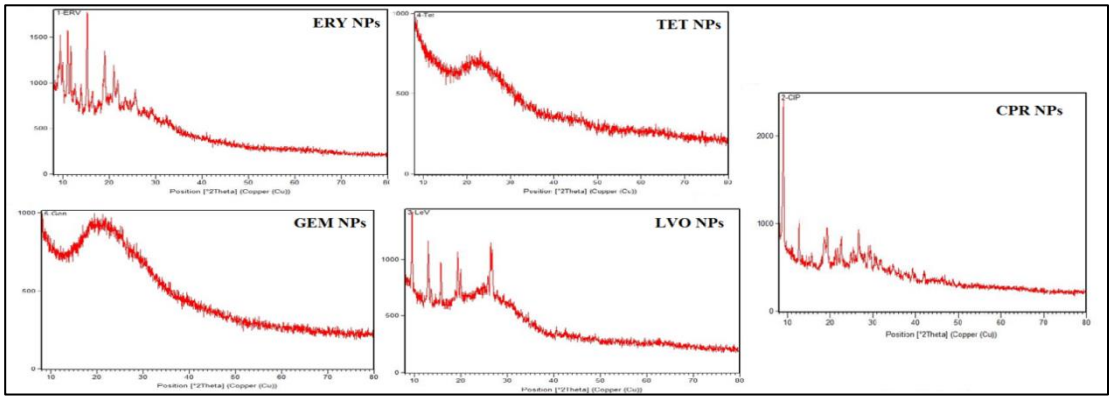

Fig (5): XRD spectroscopy of Nano antibiotic compounds

3- RESULTS AND DISCUSSION

Activation energy (E*a) values (in certain units, kJ mol^{-1}) for two different reaction, activation energy of oxidation and reduction reaction (E*a Ipa, E*a Ipc) respectively, for various Nano antibiotic in the blood medium such as erythromycin (ERY NPs), tetracycline (TET NPs), levofloxacin (LEV NPs), ciprofloxacin (CPR NPs), and gentamicin (GEM NPs).

3.1 Activation Energy (E*a) Study

Activation energy is specified as the lowest energy required for a reaction to occur.The impact of temperature was studied using the GCE in blood medium at a scan rate of 0.1 V/s to determine the activation energy (E*a). Cyclic voltammetry results showed that the peak current increased gradually over the temperature value of 25 to 50 °C. The Arrhenius equation was used to determine the (E*a) values [16, 17] 1,2,3:

$\sigma = \sigma o \exp(-Ea/RT)$ ……..1

$D = Do \exp(-Ea/RT)$ …….2

Where:

T is the temperature (K), D is the diffusion coefficient, Do is the initial diffusion coefficient, Ea is the activation energy (J/mol), R is the gas constant (8.314 J/mol·K), σ is the conductivity, and σo is the standard conductivity.

From equation 1:

$Ln (\sigma/\sigma o) = -Ea/RT$ …….3

From the linear equation (Y = mX + B), the slope (m) is (-Ea/R).

From the gradient of the linear correlation, the activation energy for the oxidation – reduction peaks present (E*a). The results of study show the cyclic voltammogram of Nano antibiotic compounds each of ERY NPs, GEM NPs, TET NPs, LEV NPs, and CPR NPs in Figures 7, 10, 13, 16, and 19 respectively.Figure 8, 11, 14, 17, and 20 show the relationship between ln(Ipa) and the reciprocal of temperature for ERY NPs, GEM NPs, TET NPs, LEV NPs, and CPR NPs respectively, while Figure 9, 12, 15, 18, and 21 show the relationship between ln(Ipc) and the reciprocal of temperature for ERY NPs, GEM NPs, TET NPs, LEV NPs, and CPR NPs respectively.

Table 1 illustrated values of activation energy of both oxidation and reduction reaction for each Nano antibiotic compounds: ERY NPs, GEM NPs, TET NPs, LEV NPs, and CPR NPs.

Table (1): Activation energy values of different Nano antibiotic in blood medium at different temperatures (25 – 50 ^{o}C)

Nano-antibiotics	E*a(Ipa) (KJ/mol.K)	Fig. No.	E*a(Ipc) (KJ/mol.K)	Fig. No.
ERY NPs	20.162	8	15.523	9
GEM NPs	9.895	11	9.618	12
TET NPs	6.9408	14	15.241	15
LVO NPs	11.532	17	12.442	18
CPR NPs	18.557	20	18.023	21

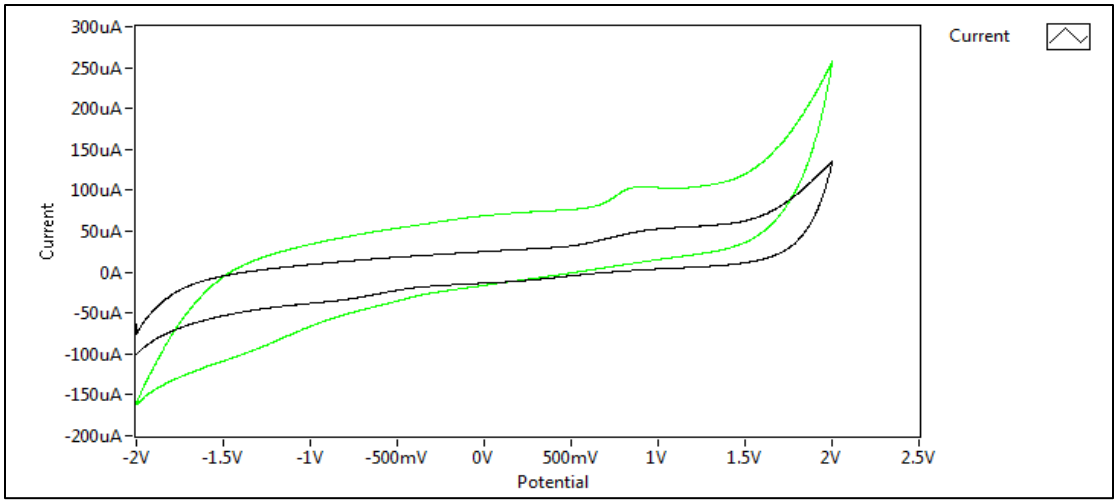

Fig (7): Cyclic voltammogram of erythromycin nanoparticles in blood mixture with a scan velocity of 0.1 Vsec-1 on GCE vs Ag/AgCl as reference electrode at temperatures between 25 and 50 degrees Celsius

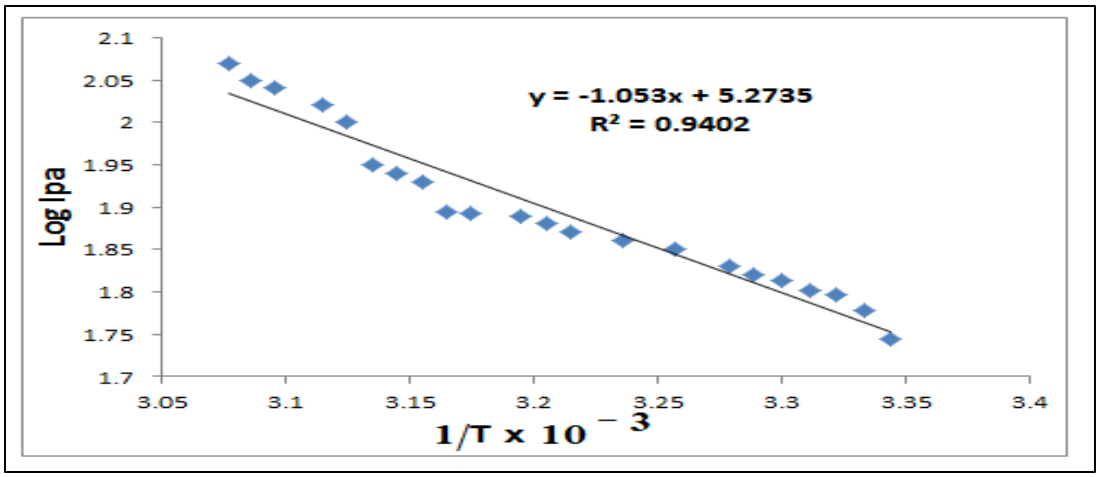

Fig (8): Plot of log(Ipa) oxidation current peak of Erythromycin nanoparticles in the blood solution vs (1/T) on GCE at scan rate (0.1 Vs^{-1}). E*a = 20.162 KJ/mol.K Erythromycin NPs (oxidation reaction)

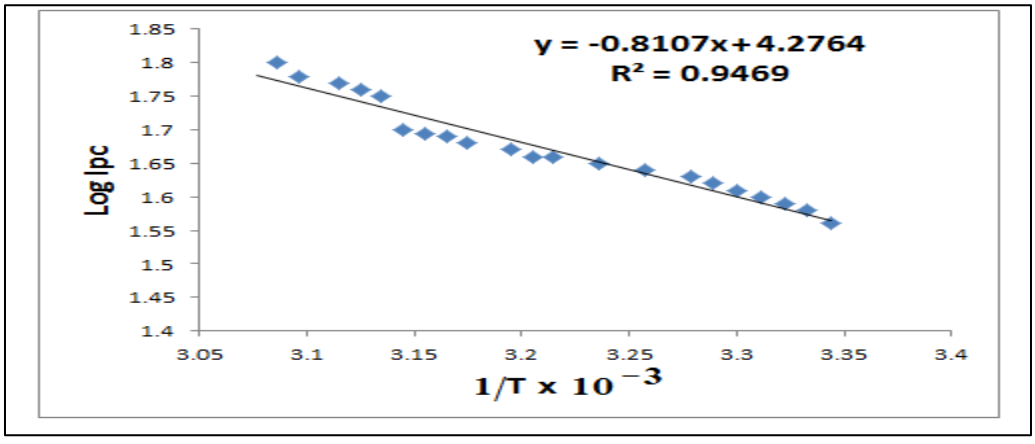

Fig (9): Plot of log(Ipc) reduction current peak of Erythromycin nanoparticles in blood mixture vs (1/T) on GCE at scan rate (0.1 Vs^{-1}). E*a = 15.523 KJ/mol.K Erythromycin NPs (reduction reaction)

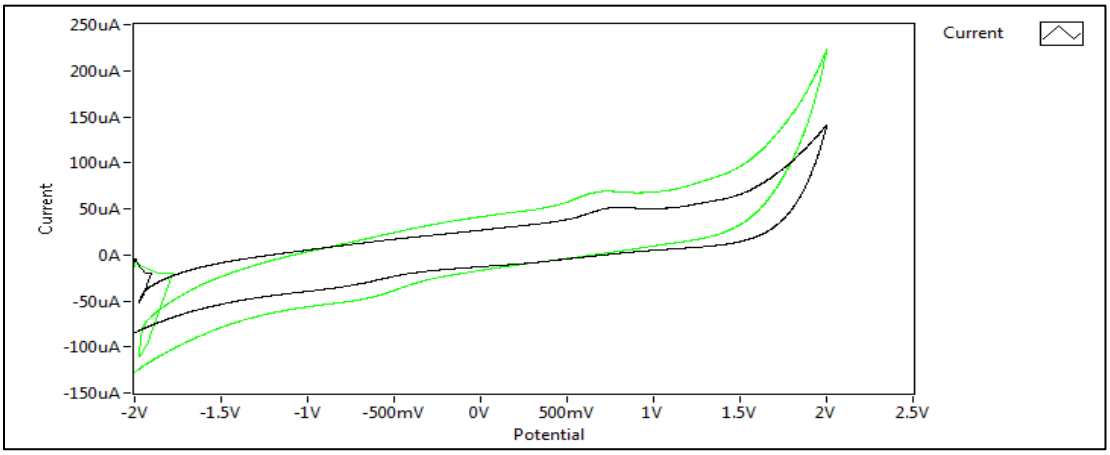

Fig (10): Cyclic voltammogram of Gentamycin nanoparticles in blood mixture at temperatures range from 25 °C to 50 °C on GCE versus Ag/AgCl as reference electrode and scan rate of 0.1 Vsec^{-1}.

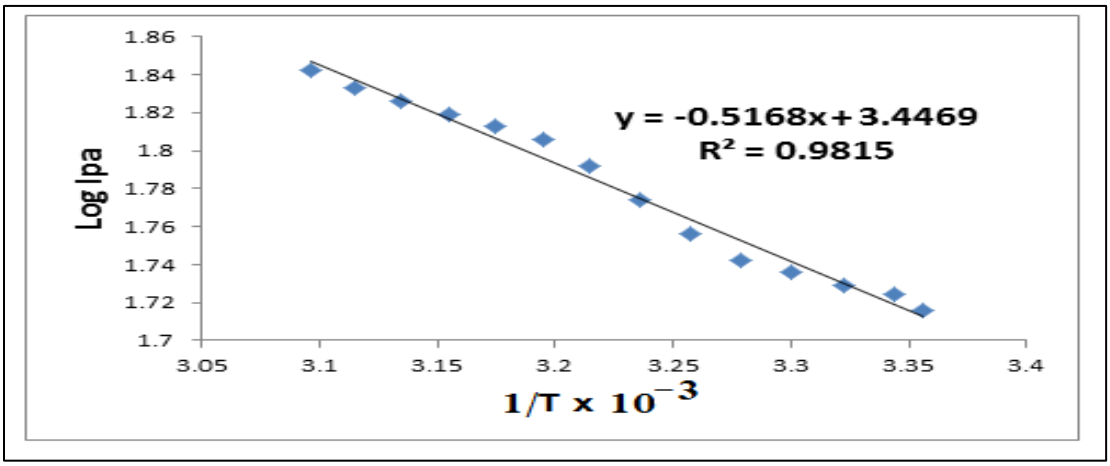

Fig (11): Plot of log(Ipa) apex of the oxidation current of Gentamycin nanoparticles in blood mixture vs (1/T) on GCE at scan rate (0.1 Vs^{-1}). E*a= 9.895 KJ/mol.K Gentamycin NPs (oxidation reaction)

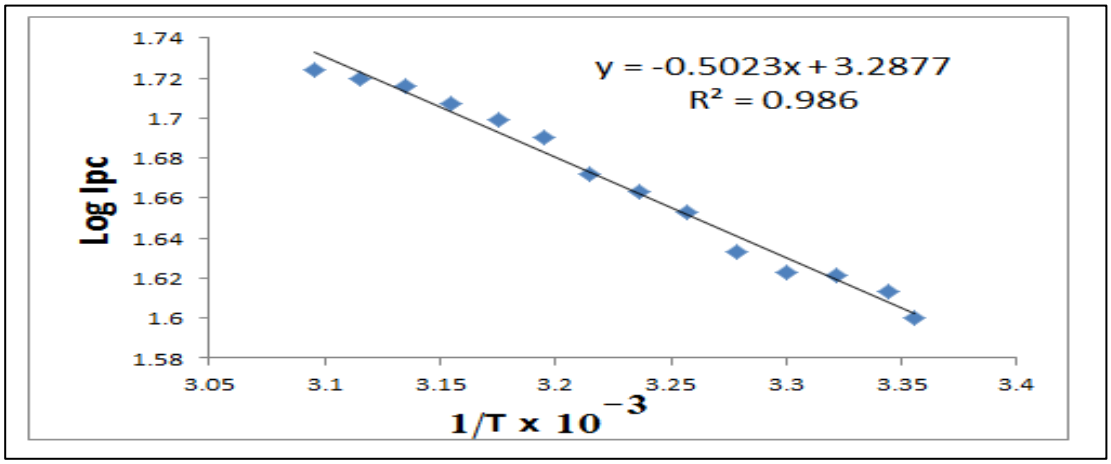

Fig (12): Plot of log(Ipc) reduction current peak of Gentamycin nanoparticles in blood mixture vs (1/T) on GCE at scan rate (0.1 Vs^{-1}). E*a = 9.618 KJ/mol.K Gentamycin NPs (reduction reaction)

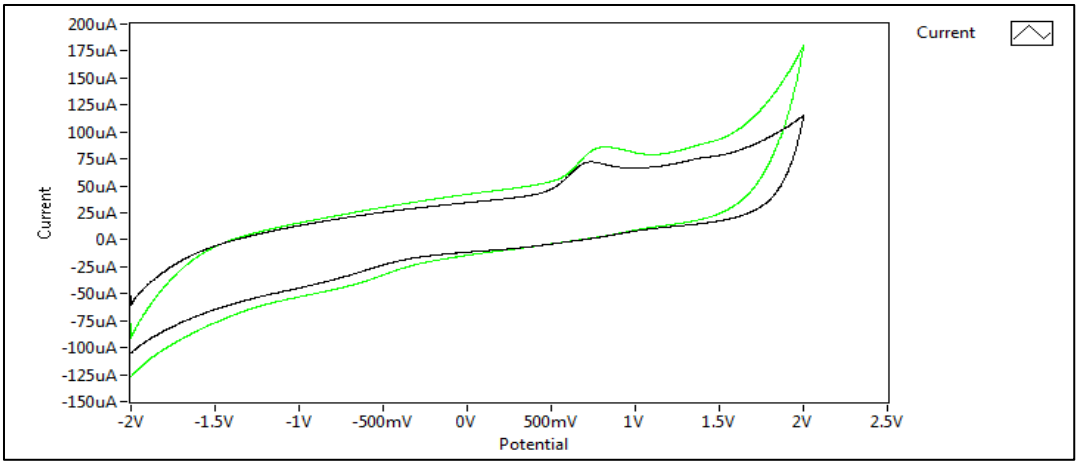

Fig (13): Cyclic voltammogram of tetracycline nanoparticles in blood mixture at temperatures range from 25 °C to 50 °C on GCE versus Ag/AgCl as reference electrode and scan rate of 0.1 $Vsec^{-1}$

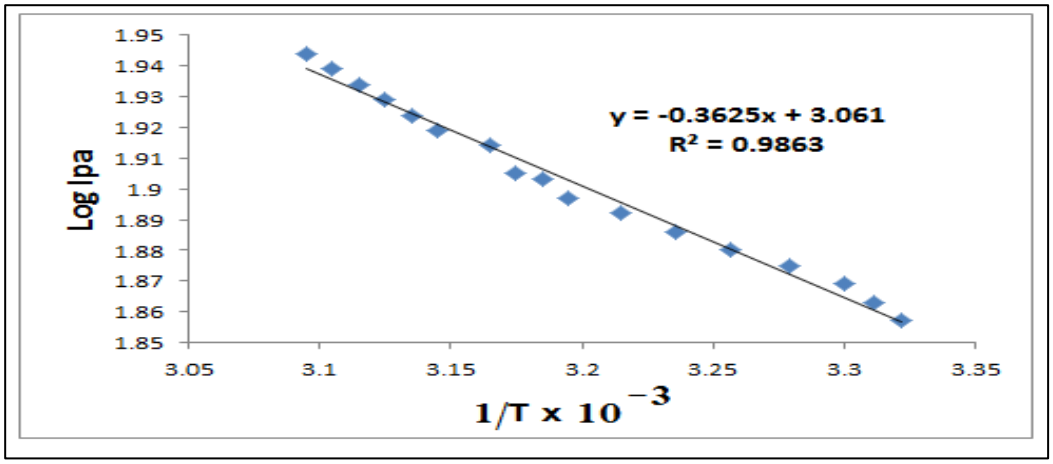

Fig (14): Plot of log(Ipa) apex of the oxidation current of tetracycline nanoparticles in blood mixture vs (1/T) on GCE at scan rate (0.1 Vs^{-1}). E*a = 6.9408 KJ/mol.K Tetracycline NPs (oxidation reaction)

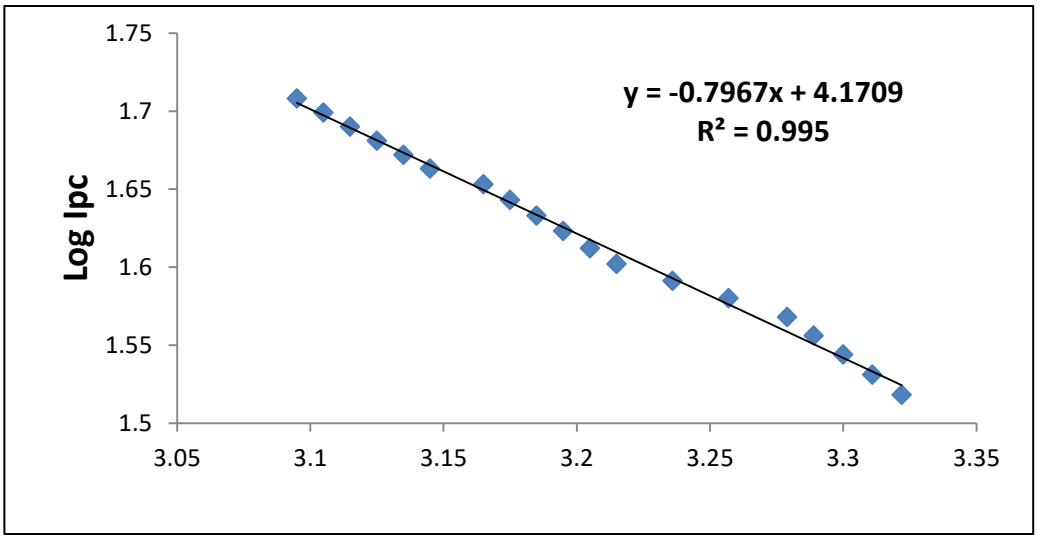

Fig (15): Plot of log(Ipc) reduction current peak of tetracycline nanoparticles in blood mixture vs (1/T) on GCE at scan rate (0.1 Vs^{-1}). E*a = 15.2411 KJ/mol.K Tetracycline NPs (reduction reaction)

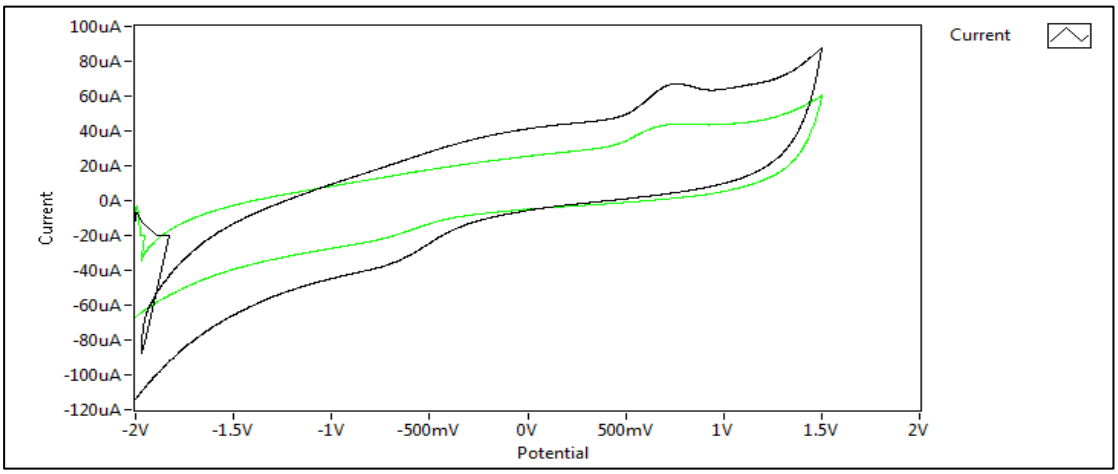

Fig (16): Cyclic voltammogram of levofloxacin nanoparticles in blood mixture at temperatures range from 25 °C to 50 °C on GCE versus Ag/AgCl as reference electrode and scan rate of 0.1 Vsec^{-1}.

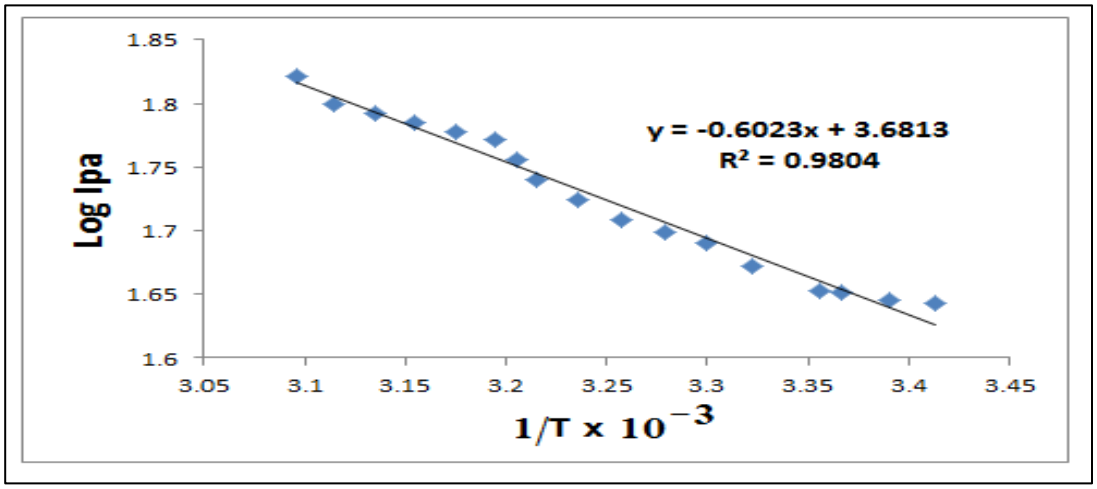

Fig (17): Plot of log(Ipa) apex of the oxidation current of levofloxacin NPs in blood medium vs (1/T) on GCE at scan rate (0.1 Vs^{-1}). E*a = 11.5323 KJ/mol.K Levo NPs (oxidation reaction)

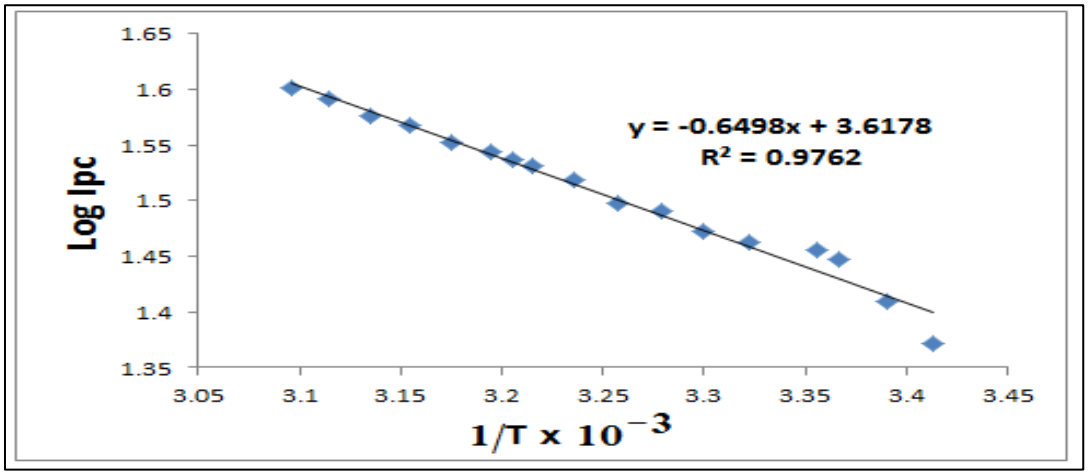

Fig (18): Plot of log(Ipc) reduction current peak of levofloxacin nanoparticles in blood solution vs (1/T) on GCE at scan rate (0.1 Vs^{-1}). E*a = 12.4418 KJ/mol.K Levo NPs (reduction reaction)

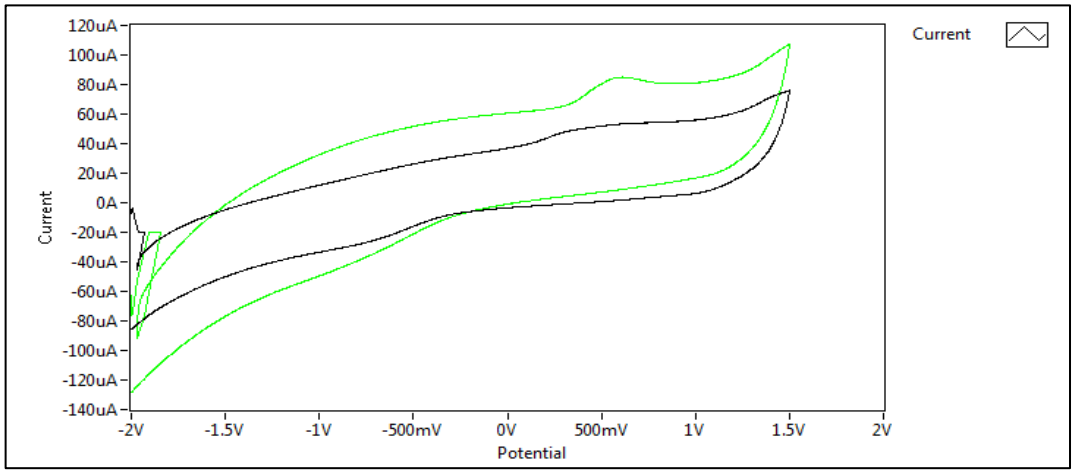

Fig (19): Cyclic voltammogram of ciprofloxacin NPs in blood medium at temperatures range from 25 °C to 50 °C on GCE versus Ag/AgCl as reference electrode and scan rate of 0.1 $Vsec^{-1}$

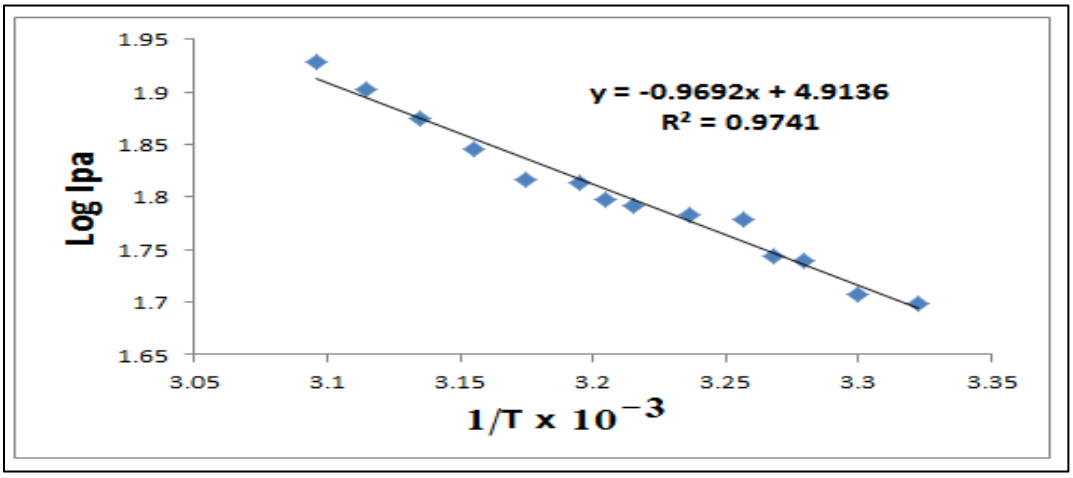

Fig (20): Plot of log(Ipa) apex of the oxidation current of ciprofloxacin NPs in blood medium vs (1/T) on GCE at scan rate (0.1 Vs−1). E*a = 18.5574 KJ/mol.K Cipro NPs (oxidation reaction)

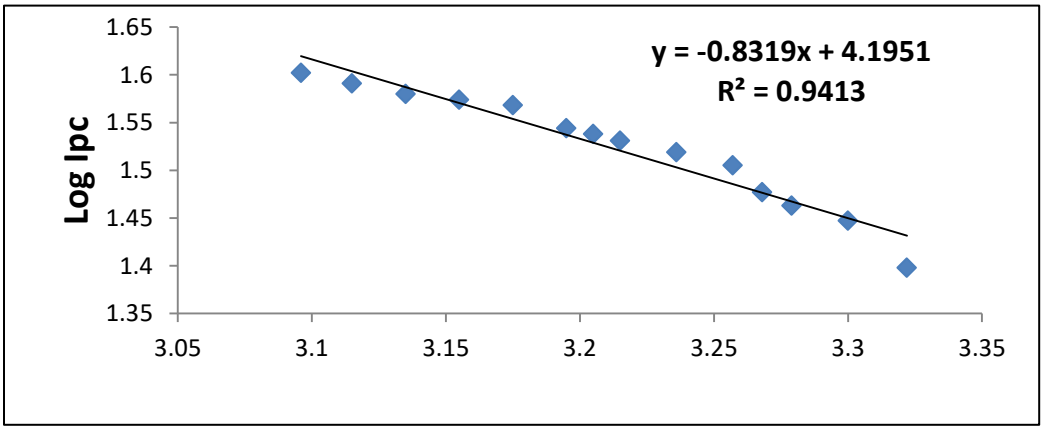

Fig (21): Plot of log(Ipc) reduction current peak of ciprofloxacin NPs in blood medium vs (1/T) on GCE at scan rate (0.1 Vs−1). E*a = 18.0232 KJ/mol.K Cipro NPs (reduction reaction)

Order of Ea* values of nanobiotic compounds

Ea*(oxidation reaction): ERY> CPR> LVO> GEM> TET

Ea*(reduction reaction): CPR>ERY = TET > LEV> GEM>

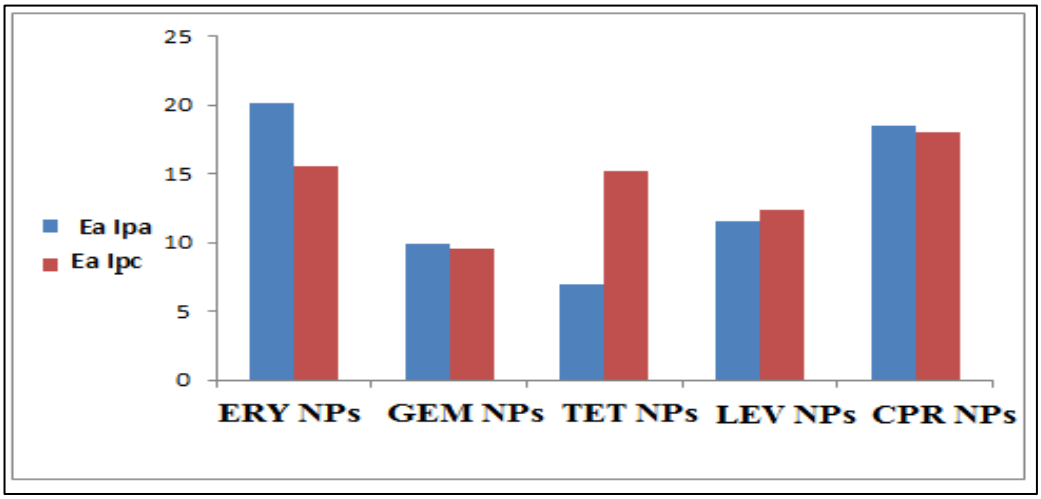

Fig (22): Activation energy of oxidation – reduction reaction of Nano antibiotic compounds.

3.2. Effect High Temperature on Nano antibiotic Compounds in Blood Matrices

As the temperature (T) increases, overcoming the energy barrier becomes easier. The higher the E*a value, the greater the effect of temperature on the reaction rate is. In the biological medium of blood, additional complexities arise: diffusion, binding/dissociation, protein coating, and others. Structural changes, localized heating, and other processes also occur. Nanoparticles often exhibit size-dependent thermal properties, variable activation barriers, surface effects, and interactions with biological molecules (such as proteins and cell membranes) that modify the effective E*a value.

Therefore, high temperatures can lead to:

1. Significantly increased reaction rates (drug release, diffusion, binding/dissociation, enzyme activity, bacterial killing) in processes with a high activation energy (Ea) compared to those with a low Ea.

2. In some cases, at very high temperatures, structural changes (structural breakdown, agglomeration, nanoparticle transformation) may unexpectedly alter the Ea value.

3. In blood, heating may improve diffusion or heat transfer, but it may also increase degradation or side effects.

Therefore, the "effect of high temperature on activation energy" is somewhat indirect: temperature does not typically alter the activation energy (energy barrier) of a simple chemical reaction (unless it causes a change in structure or state). Rather, temperature significantly alters the actual reaction rate in systems with high activation energy values [18, 19]. However, in a system consisting of nanoparticles and an antibiotic in a complex environment, the apparent activation energy may change if the reaction mechanism is altered (for example, if a different release mechanism dominates at high temperature. Furthermore, heating nanoparticle systems may lead to changes in the nanoparticles themselves (such as surface restructuring, bond breaking, and agglomeration), which may alter the activation energy.

What do the activation energy data indicate regarding temperature sensitivity and practical applications? From the table 1 and Figure 22 the results illustrated the GEM system exhibits the lowest activation energy values (9.618 and 9.895). This means that its dynamics (such as drug release and its effect on bacteria) are less sensitive to temperature changes compared to other systems. Thermal optimization will not significantly improve the reaction rate. Ciprofloxacin (CPR) has one of the highest activation energy values (18.023/18.557), so increasing the temperature would likely significantly improve the reaction rate (assuming the same reaction mechanism). Interestingly, the activation energy value of erythromycin (ERY) is higher in the Ipa environment (20.162) than in the Ipc environment (15.523). This suggests that the reaction in the Ipa environment may be more temperature-sensitive. At lower temperatures, the reaction pathway may be dominant in the Ipc environment, while at higher temperatures, the reaction may be accelerated in the Ipa environment.Tetracycline (TET) has a higher activation energy value in the Ipc environment (15.241) but a lower one in the Ipa environment (6.941). Therefore, in the Ipa environment, tetracycline is less temperature-sensitive. This may indicate a difference in the reaction mechanism between the Ipc and Ipa environments for tetracycline.Tetracycline (TET) exhibits a higher activation energy value in the Ipc

environment (15.241) but a lower one in the Ipa environment (6.941). Therefore, in the Ipa environment, tetracycline is less sensitive to temperature. This may indicate a difference in the mechanism of action between the Ipc and Ipa environments for tetracycline. Levofloxacin (LEV) has intermediate activation energy values (12.442/11.532).

As the temperature rises, we expect changes in the reaction rates of these antibiotics: those with higher activation energies will show a greater rate improvement. For example, at low temperatures, gentamicin (GEM) may outperform ciprofloxacin (CPR) (because gentamicin has a lower energy barrier). Ciprofloxacin can be easily bypassed at low temperatures, but at high temperatures, gentamicin may outperform CPR (because its reaction rate curve increases more rapidly. The difference in activation energy between the Ipc and Ipa environments for the same drug indicates the importance of the surrounding environment and the reaction mechanism [20, 21].If the sample is heated (e.g., during a fever or during diagnostic testing), antibiotics with higher activation energies will be more effective (i.e., their absorption/release/effect will be accelerated). However, caution is advised: extremely high temperatures can damage the nanoparticles or the antibiotic they contain, or alter blood proteins, potentially changing their mechanism of action (and thus their activation energy may be altered or decreased). Therefore, high temperatures tend to highlight differences in pharmacokinetics. Antibiotics with high activation energy are more sensitive to temperature and may exhibit greater increases in efficacy (or undesirable side effects) with rising temperatures [22].

4- CONCLUSION

This study demonstrated the significant effect of temperature on the electrochemical behavior and activation energy of Nano antibiotics erythromycin, tetracycline, levofloxacin, ciprofloxacin, and gentamicin in blood matrices using cyclic voltammetry. The results indicated that higher temperatures enhance the electrochemical response and facilitate electron transport, thereby reducing the activation energy of the studied Nano antibiotics. This behavior confirms the temperature-dependent kinetics of these compounds within biological environments.
Cyclic voltammetry analysis proved to be an effective and sensitive technique for assessing the thermal effect on the electrochemical activity of Nano antibiotics in complex biological matrices such as blood. The calculated activation energy values provided important insights into the stability, diffusion behavior, and reactivity of these antibiotics under different thermal conditions. Overall, the results highlight the importance of temperature in controlling the electrochemical kinetics and therapeutic efficacy of Nano antibiotics. These findings may contribute to improved analytical monitoring, the development of drug delivery systems, and a better understanding of the pharmacokinetics of antimicrobial nanoparticles in biomedical applications. Further studies involving different biological environments and nanostructures are recommended to broaden the applicability of this approach in clinical and pharmaceutical research.

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