

## Minocycline Hydrochloride: Pharmacology, Therapeutic Applications, and Emerging Perspectives

Debashis Mishra<sup>1</sup>, Ashutosh Paikaray<sup>1</sup>, Abhijeet Behera<sup>1</sup>, Chirag Kumar Pani<sup>1</sup>, Arpan Kumar Pradhan<sup>1</sup>, Diptimayee Jena<sup>1</sup>, Kirtimaya Mishra<sup>1\*</sup>

<sup>1\*</sup>School of Pharmacy & Life Sciences, Centurion University of Technology & Management, Bhubaneswar, Odisha.

Date of Submission: 01-04-2026

Date of Acceptance: 11-04-2026

### Abstract

Minocycline Hydrochloride is a second-generation semi-synthetic tetracycline antibiotic (tetracycline). Because of its broad antimicrobial spectrum and anti-inflammatory properties Minocycline is often prescribed. New evidence indicates that Minocycline also has neuroprotective, immunomodulatory and antiapoptotic effects, which can be applied beyond its traditional indications for the treatment of skin and infectious diseases. In this systematic literature review I will evaluate the physicochemical properties, mechanism of action, clinical indications, pharmacokinetics, safety profile, resistance issues, and potential applications, including new research on drug delivery systems and repurposing efforts to broaden the scope of Minocycline therapeutics.

**Keywords:** Dermatology, Clinical Indications, Antibiotic Activity, Anti-Inflammatory Activity, Delivery Systems.

### I. INTRODUCTION

Minocycline hydrochloride (second-generation semi-synthetic tetracycline) is a compound that has received continued interest from both research and clinicians because of its ability to kill bacteria (antimicrobial activity) across a wide range of organisms [1]. As of the late 1970s (when minocycline was introduced to the general public), this compound has gained renewed interest in clinical practice and research due to its ability to pass into tissues (i.e., lipid solubility). In addition, minocycline has a much longer half-life than first-generation tetracyclines and this will result in more therapeutic opportunities for treating patients and improving patient compliance [2]. While minocycline is still viewed primarily as an anti-bacterial agent that inhibits protein synthesis by reversibly binding to the 30S ribosomal subunit, it has been shown through more recent research to have many additional pharmacodynamic effects; specifically, minocycline has been demonstrated to have anti-inflammatory,

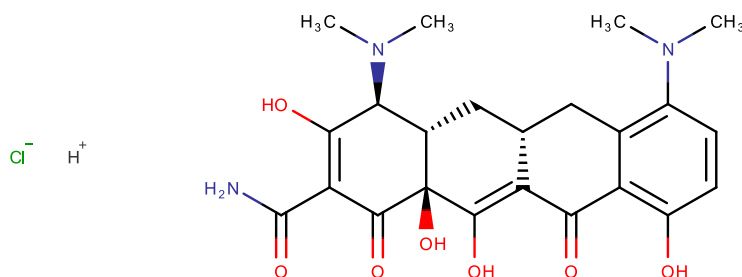
anti-apoptotic, antioxidant, and neuroprotective activities due to its ability to modulate microglial activation, inhibit matrix metalloproteinases, and attenuate the cascade of pro-inflammatory cytokines [3]. The fact that minocycline has multiple effects has fulfilled two purposes: it has provided minocycline with additional therapeutic applications in dermatological and infectious diseases, and it has increased interest in using minocycline in other types of diseases that do not have an infectious component. In the clinic, minocycline hydrochloride is currently being used as one of the primary medications for treating acne vulgaris, rosacea, and some periodontal infections, and there continues to be evidence supporting the use of minocycline for refractory/application-specific indications [4]. Preclinical and clinical studies are indicating that there may be additional benefits to using minocycline for neurological disorders (such as amyotrophic lateral sclerosis, multiple sclerosis, and ischemic stroke), autoimmune disorders, and use as a possible adjunctive therapy for cancer treatment [5]. This new thinking about minocycline shows a significant change in the way that minocycline's potential uses are defined both in terms of how it works and its therapeutic potential. While minocycline has been well documented regarding its safety and efficacy, the numerous new areas of research regarding the use of minocycline require further investigation into the safety profile, resistance to it, and dosage [6]. This review examines what is currently known regarding the pharmacology of minocycline, what established and future clinical uses it may have, and what future directions may result from increasing understanding of molecular mechanisms and increased translational research. Its hydrochloride salt improves aqueous solubility, making it suitable for oral and parenteral formulations [7].

### Chemical and Physicochemical Properties

Minocycline hydrochloride is chemically characterized as a dimethyl amino derivative of tetracycline with enhanced lipid solubility [8].

- **Molecular formula:**  $C_{23}H_{27}N_3O_7 \cdot HCl$
- **Molecular weight:** 493.94 g/mol

- Highly lipophilic compared to earlier tetracyclines
- Stable in acidic environments
- High tissue distribution, including CNS penetration



**Figure 1:** Structure of Minocycline Hydrochloride

## II. MECHANISM OF ACTION

Minocycline hydrochloride is a drug that has two different kinds of pharmacology which have increased its use and importance [9]. One main way that minocycline acts as an antibiotic is by reversibly binding to the 30S subunit of a bacterial ribosome, thereby inhibiting protein synthesis [10]. Minocycline prevents peptides from elongating by inhibiting an aminoacyl-tRNA from attaching to the five-prime end of mRNA when it is in a complex with the ribosome [11]. This action creates a bacteriostatic effect, which is effective against a wide variety of Gram-positive and Gram-negative bacteria. Due to this well-defined mechanism, minocycline has been used for many years to treat acne vulgaris, upper and lower respiratory infections, and skin and soft tissue infections [12]. In addition to its antimicrobial properties, minocycline has significant anti-

inflammatory and immunomodulatory effects, which are being emphasized in increasing numbers of studies. In addition, minocycline inhibits activation of microglia in the CNS, decreases production of pro-inflammatory cytokines (e.g., TNF- $\alpha$ , IL-1 $\beta$ ), inhibits MMPs, and inhibits the production of nitric oxide [13]. The combination of these effects results in a decrease in tissue inflammation, reduction in oxidative stress, and modulation of immune responses. The mechanisms outlined in this review show that they also allow repurposing of minocycline hydrochloride for treatment of neurodegenerative conditions, autoimmune disorders, and inflammatory diseases. The fact that minocycline hydrochloride has both antimicrobial properties and host modulating functions makes it a very capable substance that has significant potential for being repurposed and used in more advanced ways than those shown in figure 2 of the original material [14].

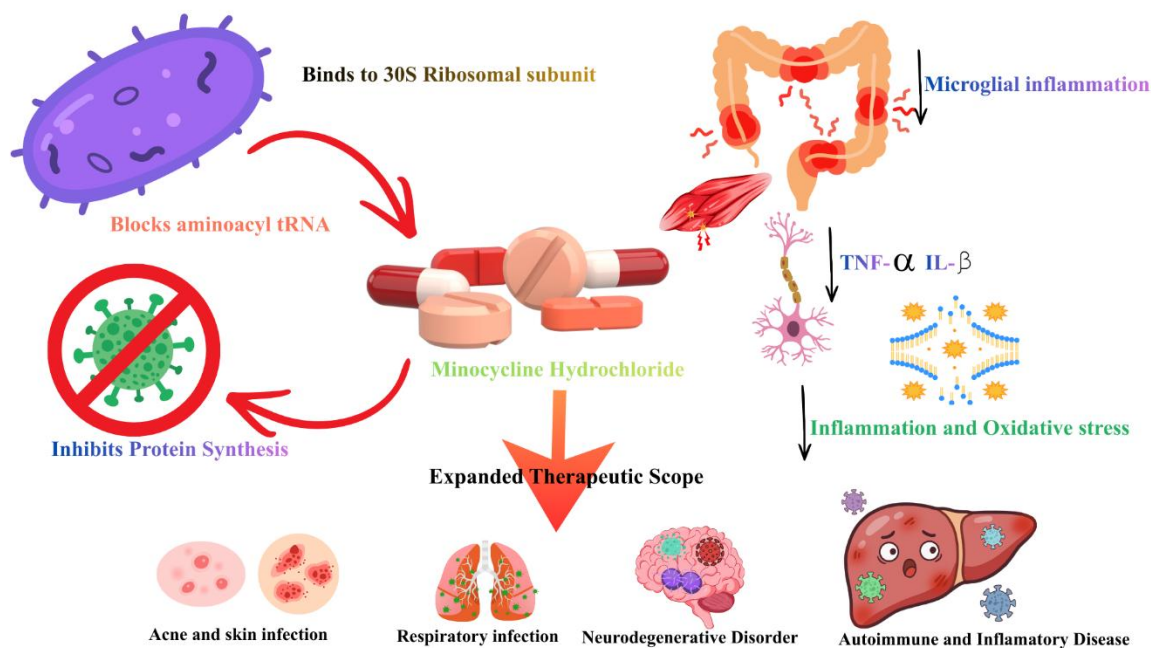


Figure 2: The dual pharmacological actions of minocycline hydrochloride

### III. PHARMACOKINETICS

- **Absorption:** Rapid and nearly complete oral absorption
- **Bioavailability:** ~90–100%
- **Protein binding:** ~70–75%
- **Half-life:** 11–22 hours
- **Metabolism:** Hepatic
- **Elimination:** Primarily biliary and fecal, minimal renal clearance

Minocycline is a tetracycline that is characterized by a large volume of distribution and high lipophilicity; hence, it has an extended half-life, allowing for once or twice per day dosing [15]. Minocycline is rapidly absorbed (>90-100%) and readily bioavailable after oral administration; therefore, it is not significantly influenced by foods, but if taken with divalent or trivalent salts (i.e., iron, calcium, magnesium), the presence of these ions may decrease its systemic availability by chelation [17]. Generally, the AUC values peak about 1-3 hours post-dose [16]. The combination of minocycline's high plasma protein binding (70-75% bound) and large volume of distribution indicate that it penetrates tissues exceptionally well due to its high lipid solubility, this drug readily crosses many biological barriers, including the BBB, so it can achieve therapeutic concentrations in the CSF [18]. Minocycline has been investigated for use in the treatment of neuroinflammatory and

neurodegenerative diseases because of this. It can also reach therapeutic concentrations in several other body compartments, including skin tissue, respiratory secretions, saliva, gingival crevicular fluid, and intracellular areas [19]. Minocycline undergoes partial hepatic metabolism to several inactive metabolites, which are then eliminated by both renal and biliary routes, with approximately 5% to 15% of the drug eliminated unchanged in urine and a large number eliminated by the feces. The half-life of elimination is between 15 hours and 23 hours, allowing it to have once-daily and twice-daily dosing schedules, which improves patient compliance [20]. Minocycline also has less need for dosage adjustments in patients with mild to moderate renal impairment than older tetracyclines due to its primarily non-renal route of elimination. Minocycline's pharmacologic characteristics (high oral bioavailability, high-volume tissue distribution, good penetration into central nervous system, and long half-life) contribute to its broad therapeutic application and continued clinical relevance [21].

### IV. CLINICAL APPLICATIONS

Minocycline hydrochloride has many potential uses beyond its original anti-microbial uses and includes treatments for dermatologic, infectious, neurologic, and rheumatologic disorders

#### Dermatological Disorders

Minocycline is still one of the main treatments for acne vulgaris, due to its dual modes of action (antibacterial and anti-inflammatory) against Cut bacterium acnes and decreasing lesions caused by inflammation. It is also commonly prescribed for papulopustular rosacea because of its immunomodulatory and anti-angiogenic functions too. Minocycline has also shown efficacy in peri-oral dermatitis, helping to heal lesions through blocking the production of inflammatory mediators [22].

### Infectious Diseases

Minocycline is a tetracycline derivative with a wide range of spectrum of activity against bacterial infections; it is used mainly to treat respiratory (lung) infections (especially if the cause of the infection is not well known) and to treat some urinary (bladder) infections (depending on how well the bacteria are responsive) [23]. It may also be used to treat some sexually transmitted infections (STIs) as an alternative to the first-line medications unless the first-line is ineffective or cannot be tolerated for some reason. Minocycline has been demonstrated to have activity against the community-acquired and some hospital-acquired strains of *Staphylococcus aureus* resistant to methicillin (MRSA); therefore, minocycline is a good option for resistant Gram-positive bacterial infections as well [24].

### Neurological and Neuroinflammatory Disorders

Due to its ability to penetrate the central nervous system readily and also suppress microglial activation, minocycline has been studied for use in multiple sclerosis with the intent to lessen inflammatory demyelination. Research into Parkinson's disease and Alzheimer's disease has been focused on evaluating the potential neuroprotective and anti-apoptotic properties of minocycline. Additionally, preliminary and experimental data have demonstrated that it may play a role in stroke-related neuroprotection, especially by decreasing inflammation around injured neurons following an ischemic event [25].

### Rheumatologic Conditions

In rheumatology, minocycline has shown that it can modify disease course in patients with rheumatoid arthritis by inhibiting metalloproteinases and reducing the production of proinflammatory cytokines. Therefore, although this drug is not used as a first-line therapy for rheumatoid arthritis, it is still being considered for patients with mild-to-moderate disease activity [26].

## V. ADVERSE EFFECTS AND SAFETY PROFILE

Minocycline HCl is well tolerated by the majority of patients; however, when taking the drug, patients can experience some form of adverse effects (AE) that can be grouped into two broad categories of AEs: dose-dependent and idiosyncratic reactions. Gastrointestinal (GI) disturbances (e.g., nausea, vomiting, epigastric discomfort), dizziness, and vestibular symptoms (e.g., vertigo, imbalance) are the most commonly reported AEs following minocycline use. Additionally, because of its greater ability to cross the blood-brain barrier compared to other tetracyclines, minocycline has a higher incidence rate of vestibular symptoms than other tetracyclines [27]. Hyperpigmented skin, nail, tooth, or mucous membrane lesions can occur in prolonged therapy with minocycline, as well as photosensitivity after exposure to ultraviolet light. Rarely, potentially serious AEs have been associated with minocycline therapy, including, but not limited to, drug-induced lupus erythematosus, autoimmune hepatitis, and systemic hypersensitivity reactions (e.g., DRESS syndrome). Therefore, extended minocycline therapy requires the physician to routinely monitor for early signs of pigmentation changes, hepatic dysfunction, or autoimmune manifestations to maintain an acceptable risk-benefit ratio in a long-term treatment regimen [28].

## VI. ANTIMICROBIAL RESISTANCE

Minocycline hydrochloride is a broad-spectrum antibiotic, but the occurrence of minocycline hydrochloride has been increasing due to the well characterized tetracycline resistance factors. The most common resistance mechanism is the development of efflux pumps produced from tet genes that pump the drug out of the bacteria causing the concentrations in the cell to fall below levels that will inhibit bacteria from growing. The second common resistance mechanism, ribosomal protection proteins (RPP), binds to the 30S ribosomal subunit and changes its shape thereby decreasing the affinity of the drug for the ribosome and allowing the bacteria to still make protein [29]. There are also some less frequent enzymes that chemically modify the antibiotic thus reducing the activity of the antibiotic. The mechanisms of resistance are often seen in cross-resistance within the tetracycline class as they all share similar structures and mechanisms of action [30]. However, due to minocycline's higher lipophilicity and increased binding to the ribosome, minocycline may retain activity against some strains of bacteria that are resistant to tetracycline depending

on the mechanism of resistance involved. The increasing spread of mobile genetic elements containing TET (ten-eleven translocation) genes makes it critical to implement antimicrobials stewardship practices. Star-Crossed prescriptive practices, appropriate dosing and susceptibility treating are essential to decreasing the development of resistance and maintaining the clinical effectiveness of minocycline hydrochloride [31].

## VII. NOVEL DRUG DELIVERY SYSTEMS

New delivery systems for drugs are developed to prolong the effectiveness of the antibiotic-minocycline hydrochloride. To enhance the effectiveness and lower the side effects of this antibiotic by developing new drug formulations [32]. An example of such a novel drug delivery system would involve liposomal formulations that entrap minocycline within a phospholipid bilayer, providing a more stable formulation and extended duration of action in tissue with accumulation in areas of inflammation and infection. There are also new delivery formulations utilizing polymeric nanoparticles, solid lipid nanoparticles and nanostructured lipid carriers include the use of these types of drug delivery systems to create a controlled release of drugs, enhance cellular uptake, and increase the permeability of drugs across biological membranes thereby increasing the amount of drug available for therapeutic action at sites of disease [33]. Finally, new ocular insert formulations and systems have been developed to gel upon contact with the tear film that will help slow down the elimination of drugs from the precorneal area of the eye in order to prolong the duration of action and provide increased contact time with the cornea. These delivery systems also provide effective local treatment of ocular infections and inflammatory disease and minimize systemic exposure through localized treatment [34]. Oral forms of minocycline include controlled-release tablets and capsules that help provide consistent plasma levels through less frequent dosing. These advanced formulations enhance patient compliance, reduce adverse effects due to increased dosing intervals, and optimize the pharmacologic properties of minocycline by increasing bioavailability, lowering systemic toxicity, and providing for localized or sustained release. As such, these advanced delivery systems provide a significant advancement to improving treatment outcomes for minocycline (hydrochloride), as well as broadening the scope of clinical applications for minocycline [35].

## ANALYTICAL METHODS FOR QUANTIFICATION OF MINOCYCLINE HYDROCHLORIDE

There are a variety of analytical methods available to discover how much minocycline hydrochloride is included within both pharmaceutical formulations and biological matrices. One such method is based on using UV spectrophotometry (around 354 nm). While it is inexpensive and simple enough for daily use, it does suffer from low specificity compared to a more precise reverse phase HPLC (RP-HPLC) method that uses UV detection (around 350 nm) with C18 columns. It's more sensitive, repeatable and precise than UV spectrophotometry; therefore, RP-HPLC is commonly used to provide product quality control on tablets and liquid plasma samples. Another example of an HPLC method specifically designed to identify stability and degradation of minocycline through UV detection (254 nm) has been developed in order to completely separate degradation products created from forced degradation of minocycline hydrochloride [36]. Advanced bioanalytical methods are also available utilizing UPLC-MS/MS and LC-MS/MS technologies; these two techniques have orders of magnitude greater sensitivity (nanogram threshold) than other analytical techniques allowing for reliable determination of pharmacokinetic profile of animals and humans in plasma. The HPLC-DAD method allows for the ability to detect multiple wavelengths, allowing for simultaneous detection and characterization of complex matrices (serum, urine). All of these analytical approaches demonstrate the evolution of methods available for the quantitation and PK evaluation of minocycline from simple spectrophotometric assays to complex, sensitive mass spectrometric techniques, as can be seen in Table 1 [37].

**Table 1:** Quantitative analysis of minocycline hydrochloride from pharmaceutical formulations and biological specimens, with emphasis on UV spectrophotometry, HPLC, and LC-MS/MS quantification methodologies, with regard to sensitivity, dynamic range, and method performance.

Method	Instrument / Wavelength / Mode	Sample Matrix	Column / Mobile Phase	LOD / LOQ	Linear Range	Key Findings	Reference
UV Spectrophotometry	UV at 354 nm	Pharmaceutical formulations	NA	LOD: 0.2 µg/mL	1–10 µg/mL	Simple, cost-effective assay but lower specificity	38
HPLC-UV (RP-HPLC)	UV @ 350 nm; RP-C18	Tablet & plasma	Acetonitrile: phosphate buffer	LOD: 0.05 µg/mL; LOQ: 0.15 µg/mL	0.1–20 µg/mL	Good resolution and reproducibility; suitable for routine QC	39
HPLC-UV (Stability-Indicating)	UV @ 254 nm; RP-C18	Forced degradation studies	Methanol: water (pH adjusted)	LOD: 0.03 µg/mL	0.05–25 µg/mL	Effective for degradation product separation	40
UPLC-MS/MS	ESI-MS/MS, positive ion	Human plasma	UPLC BEH C18; gradient	LOD: 0.5 ng/mL	1–2000 ng/mL	High sensitivity & selectivity, lower sample volume	41
LC-MS/MS (Pharmacokinetic Analysis)	ESI+; MRM	Rat plasma	C18; ACN: aqueous	LOD: 0.2 ng/mL; LOQ: 0.8 ng/mL	0.8–1000 ng/mL	Robust PK profiling in preclinical studies	42
LC-MS (High-Resolution)	HR-MS; QTOF	Skin micro dialysate	C18; gradient	LOD: 1 ng/mL	5–1000 ng/mL	Effective for skin penetration studies	43
HPLC-DAD (Photodiode Array)	DAD scan 200–400 nm	Serum & urine	RP-C18; isocratic	LOD: 0.1 µg/mL	0.1–15 µg/mL	Useful for multi-component separation	44

## VIII. DRUG REPURPOSING AND FUTURE DIRECTIONS

Due to minocycline hydrochloride's complex anti-inflammatory, immunomodulatory, and neuroprotective effects, research into its possible applications as a drug repurposed for non-infectious diseases has gained considerable attention. Currently, research is being conducted for the use of minocycline as an adjunctive treatment in psychiatric disorders, such as major depressive disorder and schizophrenia, in which alterations in neuroinflammatory pathways may lead to improved clinical outcomes. In oncology, minocycline may exhibit potential anti-metastatic and anti-angiogenic effects, in part, by inhibiting the activity of matrix metalloproteinases and inhibiting inflammation associated with a tumour. Emerging evidence also suggests that minocycline may have a supportive role in the treatment of certain viral infections. This occurs through attenuation of excessive host

inflammatory responses rather than through any direct antiviral effects on the virus itself. Research into minocycline's ability to deliver medications to tissues effectively, if developed through local anti-inflammatory delivery systems, may potentially result in the treatment of ocular inflammatory diseases as well. However, although preclinical data supports the use of minocycline in a variety of expanded clinical indications and early clinical trials have been promising, there is still a need for well-designed, adequately powered, randomized placebo-controlled trials to fully define its therapeutic uses, optimize dosing and administration, and evaluate long-term safety across a variety of expanded therapeutic uses [45].

## IX. CONCLUSION

Minocycline is still a very important clinical treatment and has many new indications for treatment along with the establishment of its systemic anti-inflammatory and neuroprotective action. These

effects contribute to making minocycline a very suitable drug candidate for repurposing as a treatment; therefore, it is crucial to have ongoing antimicrobial stewardship programs, continued safety monitoring of the drug, and adequate clinical evidence of the use of minocycline will be necessary to make sure that minocycline is used appropriately in the future.

### REFERENCES

- [1]. Rusu A, Buta EL. PHARMACEUTICS, *Pharmaceutics* 2021; 13(12):2085.
- [2]. Kounatidis D, Dalamaga M, Grivakou E, et al. BIOMOLECULES, *Biomolecules* 2024; 14(7):783.
- [3]. Nagarakanti S, Bishburg E. BASIC & CLINICAL PHARMACOLOGY & TOXICOLOGY, *Basic Clin Pharmacol Toxicol* 2016; 118(1):4–8.
- [4]. Lashinsky JN, Henig O, Pogue JM, et al. INFECTIOUS DISEASES AND THERAPY, *Infect Dis Ther* 2017; 6(2):199–211.
- [5]. Martins AM, Marto JM, Johnson JL, et al. ANTIBIOTICS, *Antibiotics* 2021; 10(7):757.
- [6]. Mishra K, Jena D, Mishra D. JOURNAL OF PHARMA INSIGHTS AND RESEARCH, *J Pharma Insights Res* 2025; 3(6):059–066.
- [7]. Bahrami F, Morris DL, Pourgholami MH. MINI REVIEWS IN MEDICINAL CHEMISTRY, *Mini Rev Med Chem* 2012; 12(1):44–52.
- [8]. Garrido-Mesa N, Zarzuelo A, Gálvez J. BRITISH JOURNAL OF PHARMACOLOGY, *Br J Pharmacol* 2013; 169(2):337–352.
- [9]. Jena D, Sahoo S, Mohanty P, Mishra D, Mishra K. ASIAN JOURNAL OF RESEARCH IN PHARMACEUTICAL SCIENCES, *Asian J Res Pharm Sci* 2025; 15(4):409–417.
- [10]. Allen JC. ANNALS OF INTERNAL MEDICINE, *Ann Intern Med* 1976; 85(4):482–487.
- [11]. Manna PK, Sarangi B, Mishra K, Mohanta GP. EUROPEAN POLYMER JOURNAL, *Eur Polym J* 2020; 122:109366.
- [12]. Ladhani S, Garbash M. PEDIATRIC DRUGS, *Pediatr Drugs* 2005; 7(2):77–102.
- [13]. Sunderkötter C, Herrmann M, Jappe U. JDDG, *J Dtsch Dermatol Ges* 2006; 4(1):10–27.
- [14]. Bradley JS, Sauberan JB. PRINCIPLES AND PRACTICE OF PEDIATRIC INFECTIOUS DISEASE, 2012; 1453–1484.
- [15]. Balamurugan K, Mishra K, Suresh R. PHARMA INNOVATION JOURNAL, *Pharma Innov J* 2018; 7(8):357–361.
- [16]. Barza M, Brown RB, Shanks C, et al. ANTIMICROBIAL AGENTS AND CHEMOTHERAPY, *Antimicrob Agents Chemother* 1975; 8(6):713–720.
- [17]. Reddy MR, Mishra K, Suresh R. INTERNATIONAL JOURNAL OF PHARMA RESEARCH AND HEALTH SCIENCES, *Int J Pharma Res Health Sci* 2018; 6(1):2303–2307.
- [18]. Mishra K, Jena D, Prasanth D, Jabeen A, Sahoo S, Bhatta P, Jeeya A. INTERNATIONAL JOURNAL OF PHARMACOGNOSY AND LIFE SCIENCE, *Int J Pharmacogn Life Sci* 2023; 4(1):121–126.
- [19]. Fayazi M, Rostami M, Amiri Moghaddam M, et al. JOURNAL OF DRUG TARGETING, *J Drug Target* 2025; 33(5):612–647.
- [20]. Hîncu S, Apetroaei MM, Ştefan G, et al. PHARMACEUTICS, *Pharmaceutics* 2024; 16(9):1137.
- [21]. Brogden RN, Speight TM, Avery GS. DRUGS, *Drugs* 1975; 9(4):251–291.
- [22]. Jonas M, Cunha BA. THERAPEUTIC DRUG MONITORING, *Ther Drug Monit* 1982; 4(2):115–146.
- [23]. Howard R, Zubko O, Bradley R, et al. JAMA NEUROLOGY, *JAMA Neurol* 2020; 77(2):164–174.
- [24]. Mishra K, Jena D, Mishra D. INTERNATIONAL JOURNAL OF PHARMACEUTICAL RESEARCH AND APPLICATIONS, *Int J Pharm Res Appl* 2025; 10(6):1448–1456.
- [25]. Zhanel GG, Homenuik K, Nichol K, et al. DRUGS, *Drugs* 2004; 64(1):63–88.
- [26]. Tilley BC, Alarcon GS, Heyse SP, et al. ANNALS OF INTERNAL MEDICINE, *Ann Intern Med* 1995; 122(2):81–89.
- [27]. Dominic MR. CURRENT DRUG SAFETY, *Curr Drug Saf* 2021; 16(3):309–321.
- [28]. Mishra K, Das PR, Subhadarshinee S, Jena D. INTERNATIONAL JOURNAL OF PHARMACEUTICAL RESEARCH AND APPLICATIONS, *Int J Pharm Res Appl* 2025; 10(5):782–795.
- [29]. Franceschi F, Duffy EM. BIOCHEMICAL PHARMACOLOGY, *Biochem Pharmacol* 2006; 71(7):1016–1025.



- [30]. Chopra I, Roberts M. MICROBIOLOGY AND MOLECULAR BIOLOGY REVIEWS, *Microbiol Mol Biol Rev* 2001; 65(2):232–260.
- [31]. Jurado-Rabadán S, de la Fuente R, Ruiz-Santa-Quiteria JA, et al. BMC VETERINARY RESEARCH, *BMC Vet Res* 2014; 10(1):155.
- [32]. Javed S, Kohli K. CURRENT DRUG DELIVERY, *Curr Drug Deliv* 2010; 7(5):398–406.
- [33]. Huang Z, Kłodzińska SN, Wan F, et al. DRUG DELIVERY AND TRANSLATIONAL RESEARCH, *Drug Deliv Transl Res* 2021; 11(4):1634–1654.
- [34]. Barar J, Aghanejad A, Fathi M, et al. BIOIMPACTS, *Bioimpacts* 2016; 6(1):49.
- [35]. Singh S, Khanna D, Kalra S. CURRENT MOLECULAR PHARMACOLOGY, *Curr Mol Pharmacol* 2021; 14(6):1046–1065.
- [36]. Patel RP, Patel MM, Shelat PK. INTERNATIONAL JOURNAL OF PHARMACEUTICAL SCIENCES REVIEW AND RESEARCH, *Int J Pharm Sci Rev Res* 2011; 10(1):67–71.
- [37]. El-Bardicy SAM, Fahmy UA. JOURNAL OF CHROMATOGRAPHIC SCIENCE, *J Chromatogr Sci* 2014; 52(6):485–492.
- [38]. Sharma B, Kaur H. ANALYTICAL CHEMISTRY LETTERS, *Anal Chem Lett* 2016; 6(3):257–267.
- [39]. Zhang X, Zhang J, Gao Y. JOURNAL OF PHARMACEUTICAL AND BIOMEDICAL ANALYSIS, *J Pharm Biomed Anal* 2017; 140:15–22.
- [40]. Wei H, Li M, Liu Y. BIOMEDICAL CHROMATOGRAPHY, *Biomed Chromatogr* 2018; 32(7):e4193.
- [41]. Lopez-Gonzalez R, et al. ANALYTICAL AND BIOANALYTICAL CHEMISTRY, *Anal Bioanal Chem* 2019; 411(19):4979–4989.
- [42]. Kumar A, Singh K. BIOMEDICAL ANALYSIS, *Biomed Anal* 2020; 23(4):1123–1131.
- [43]. Serb AF, Georgescu M, Onulov R, et al. MOLECULES, *Molecules* 2024; 29(6):1336.
- [44]. Bozal-Palabiyik B, Erkmen C, Demir E, et al. ADVANCES IN HEALTH AND DISEASE, *Adv Health Dis* 2020; 53.
- [45]. Bawage SS, Tiwari PM, Pillai S, et al. VIRUSES, *Viruses* 2019; 11(8):739.