Natural Resources for Human Health
eISSN: 2583-1194

Original Research

Received 16 April 2026
Revised 24 May 2026
Accepted 22 June 2026

Natural Resources for Human Health 2026, Vol. 6 (3s): 162–174

KEYWORDS:
Noise-induced hearing loss, mining, cochlear injury, otoprotection, antioxidants, hearing conservation.

Noise-Induced Hearing Loss in Mining: Biological Mechanisms and Emerging Pharmacological Otoprotection

Abida Khan[1], Howayada Mahany Mostafa[2], Syed Raziuddin Quadri[3], Mohd Imran[1*]

[1] Center for Health Research, Northern Border University, Arar 73213, Saudi Arabia.
[2] Department of Chemistry, College of Science, Northern Border University, Arar, Saudi Arabia.
[3] Department of Medical Laboratory Technology, College of Applied Medical Sciences, Northern Border University, Arar 91431, Saudi Arabia.
* Corresponding author: imran.pchem@gmail.com (Mohd Imran)

ABSTRACT: Noise-induced hearing loss (NIHL) is a major occupational health problem, especially within the mining industry, where workers are frequently exposed to hazardous levels of occupational noise from drilling, blasting, crushing, and heavy machinery. While engineering controls, hearing protection devices, and audiological surveillance are key preventive measures, they may not completely prevent cochlear injury. This review focuses on the epidemiology, biology, and novel pharmacological preventive and mitigating otoprotective strategies for mining-associated NIHL. Excessive noise exposure causes oxidative stress, mitochondrial dysfunction, inflammation, excitotoxicity, synaptic damage, and hair cell injury, thereby providing a biological rationale for studying otoprotective therapies. Experimental studies have demonstrated promising effects of antioxidants, including N-acetylcysteine, D-methionine, and ebselen, as well as anti-inflammatory, metabolic, and regenerative therapies, but human studies remain limited and inconclusive. Limitations in effective drug delivery to the cochlea, the long-term safety of repeated drug administration, the lack of validated biomarkers, and the absence or near absence of mining-specific pharmacological trials are significant barriers. Pharmacological intervention should thus be considered investigational, additional to, and not a substitute for comprehensive hearing-conservation programs. Future studies should prioritize longitudinal occupational research, biomarker-guided risk assessment, mining-specific clinical trials, and clinically meaningful hearing outcomes.

1. INTRODUCTION

Noise-induced hearing loss (NIHL) is a form of sensorineural hearing loss caused by acute exposure to intense sound or by prolonged exposure to hazardous noise levels [1]. It develops gradually, and the symptoms go unnoticed until workers begin to notice tinnitus, communication problems, or reduced ability to hear speech in noisy places. NIHL is among the most prevalent occupational health conditions worldwide and continues to be an important cause of preventable disability and diminished quality of life. It is estimated that about 5% of the world's population suffers from disabling hearing loss, and 16% of disabling hearing loss among adults is due to occupational noise exposure [1, 2]. The condition is largely irreversible, and mammalian cochlear hair cells have a limited ability to regenerate after injury [3].

The mining industry is a high-risk occupation for NIHL [4]. The results from comparative studies and meta-analyses suggest that workers in mining occupations are more likely to have hearing loss than those in many other occupations. It can also differ significantly across underground and surface mines, depending on the equipment, operations, and acoustic environments

encountered. Preventing NIHL can be difficult in resource-limited mining operations, especially when the various strategies for noise monitoring, engineering controls, hearing protection devices, worker education, audiometric surveillance, and occupational record-keeping are not integrated into a coordinated hearing-conservation program. A study conducted at a mining company in Ghana found that 68.6% of workers were exposed to noise levels classified as unacceptable [5]. Evidence also indicates that hearing-conservation measures in African mining settings are often implemented separately rather than as part of a comprehensive program. Such fragmentation may reduce their effectiveness, limit regulatory oversight, and delay the early identification of occupational hearing loss [6].

Controlling noise at its source remains the most effective approach for preventing NIHL. However, growing understanding of the roles of oxidative stress, inflammation, excitotoxicity, mitochondrial dysfunction, and delayed cochlear cell death has increased interest in pharmacological agents as adjunctive protective strategies when hazardous noise exposure cannot be eliminated. A systematic review of 11 prospective clinical studies involving 701 participants reported potentially beneficial effects of interventions such as carbogen and ebselen under specific experimental conditions [7]. Importantly, substantial differences in study design, treatment timing relative to noise exposure, participant characteristics, noise-exposure protocols and outcome-assessment methods prevented the formulation of definitive clinical recommendations.

There are important limitations to applying existing evidence to mining populations because most pharmacological studies have been conducted in animal models, military personnel, healthy volunteers, or participants exposed to noise under controlled experimental conditions. These noise-exposure settings differ substantially from those encountered in mining operations, where it may be continuous, intermittent, impulsive, or highly variable. Mining workers may also experience simultaneous exposure to vibration, dust, heat, chemicals, and potentially ototoxic substances or medications. Consequently, the efficacy, long-term safety, feasibility, and occupational implications of pharmacological otoprotection among mining workers remain uncertain.

This review summarizes the epidemiological burden and biological mechanisms of NIHL, with particular attention to occupational exposure in mining environments. It critically evaluates established, emerging, and novel pharmacological approaches to the prevention and treatment of NIHL. This review also highlights current developments in inner-ear drug delivery, the challenges associated with implementation in occupational settings, and the potential contribution of pharmacologic therapies to comprehensive hearing-conservation programs.

2. MINING-RELATED NOISE EXPOSURE, EPIDEMIOLOGY, AND COCHLEAR INJURY

This section provides an overview of the principal noise sources in mining, the epidemiological burden and occupational health consequences of noise-induced hearing loss (NIHL), and the biological mechanisms underlying cochlear injury.

2.1 Mining Noise Exposure, Epidemiological Burden, and Occupational Consequences

Mining workers are exposed to noise from drilling, blasting, crushing, grinding, milling, haulage operations, ventilation systems, conveyors, compressors, and diesel-powered equipment. High-intensity impulsive noise is generated primarily by blasting and rock drilling, whereas most other noise sources, such as crushers, mills, haul trucks, conveyors, and ventilation systems, produce continuous or fluctuating noise exposure [8].

The magnitude of the occupational noise exposure in mining is highlighted by findings from Chinese metal mines, where average noise exposure levels of 93.5 dB(A), 90.4 dB(A), and 86.2 dB(A) were reported among excavation workers, mill operators, and crusher operators, respectively [9]. Hazardous noise exposure has also been identified among workers operating haul trucks, load–haul–dump machines, and longwall shearers [10, 11]. Prolonged exposure to noise above recommended occupational exposure limits can result in permanent sensorineural hearing loss. In contrast, high-intensity impulsive noise can cause immediate mechanical damage and progressive metabolic injury within the cochlea [12].

Underground and surface mines have different noise-exposure patterns. In underground mines, the continuous operation of ventilation systems, proximity to machinery, reverberation from rock surfaces, and limited working space can contribute to workers' cumulative noise exposure. According to a study of 27 metal-mining enterprises in China, 36.5% of all noise measurements exceeded 85 dB(A), while the proportion exceeding the occupational limit was greater in underground mining (42.4%) [9]. Surface mining also presents significant acoustic risks to workers operating near drills, crushers, haulage vehicles, and other mobile machinery [8, 13]. Therefore, underground and surface mines should be considered separate acoustic environments, as they have distinct acoustic properties and require different exposure assessment and control measures.

Average noise level is not the only factor determining the risk of hearing damage. Noise intensity (dB), exposure duration, frequency content, impulsiveness, distance from the noise source, and recovery time between exposures all affect cochlear stress. Thus, workers with equal time-weighted average exposures may sustain different degrees of auditory damage. Furthermore, the effects of multiple short-duration peaks, impulsive noise, and inadequate recovery between shifts may not be adequately reflected in routine average noise measurements [12].

The prevalence of hearing loss reported among miners depends on the characteristics of the mining workforce, the mining method, the method used to assess noise exposure and hearing loss, and the criteria and definitions used to identify hearing loss. In the United States, the prevalence of hearing loss among workers in mining occupations was 24% between 2006 and 2015, compared with 16% among all workers [14]. In a subsequent meta-analysis, the prevalence of hearing loss among miners was estimated at 22.9%-47%, making mining one of the occupations with the highest reported prevalence of hearing loss [4]. However, comparisons between studies are not straightforward due to variation in audiometric thresholds, diagnostic criteria, and measured frequency ranges.

In the Asia-Pacific region, coal miners also have hearing loss. This high prevalence is often linked to the continued use of older machinery, inconsistent enforcement of occupational safety regulations, limited monitoring of hearing-protection use, and inadequate worker training [13, 15]. Findings from other mining operations also show that inadequate knowledge and training and unfavorable attitudes toward hearing protection may limit the effectiveness of preventive measures [16, 17].

Other factors affecting susceptibility to NIHL include age, sex, smoking, cardiovascular disease, metabolic disease, previous ear conditions, and the use of ototoxic drugs [12, 18]. These risk factors are also found among broader occupational groups. A systematic review of 71,865 workers exposed to noise in China revealed an NIHL prevalence of 21.3%, with 30.2% of workers having high-frequency NIHL [18]. Higher noise levels, longer exposure duration, older age, and combined chemical exposure were associated with an increased risk of hearing loss. The review included all workers across various industries, and not just miners. The results indicate that hearing damage is caused by a combination of the workplace and the individual's susceptibility.

Other occupational exposures for miners include solvents, welding fumes, carbon monoxide, diesel exhaust, metals, vibration, and ototoxic medication [19]. Combined exposure to noise and some chemicals can lead to greater high-frequency hearing loss than noise exposure alone [18, 19]. In communities with high levels of tuberculosis (TB) or HIV, ototoxic medications also raise concern [19, 20]. Therefore, a hearing-conservation program that emphasizes noise exposure may underestimate the potential effects of co-occurring exposures to chemicals, pharmacologic substances, and other physical hazards.

NIHL may have effects beyond measurable changes in audiometric thresholds. Influenced workers can experience tinnitus, hearing difficulties in noisy environments, difficulty localizing sound, listening fatigue, and reduced ability to hear alarms or verbal instructions [21]. These effects are especially valuable in the mining industry, where the ability to warn of moving machinery, provide spoken safety instructions, and use warning signals is paramount in preventing workplace accidents. One study estimated that 20.3% of injury cases in the study population were attributable to full-shift noise exposure at or above 88 dB(A) [22]. Thus, hearing-surveillance programs should evaluate tinnitus and functional communication problems and conduct conventional pure-tone audiometry.

2.2 Cochlear Injury, Synaptopathy, and the Therapeutic Window

The intensity and pattern of exposure influence the biological effects of mining noise. Very loud sounds can mechanically damage stereocilia, sensory cells, supporting cells, and cochlear membranes. In contrast, chronic occupational exposure can lead to persistent metabolic and cellular stress. Outer hair cells are especially sensitive and particularly vulnerable to damage, which can result in early high-frequency hearing loss. Inner hair cells, the stria vascularis, auditory synapses, and spiral ganglion neurons may also be affected by prolonged noise exposure [23].

Noise exposure increases metabolic demand within the cochlea and promotes the production of reactive oxygen and nitrogen species. If cellular antioxidant mechanisms are insufficient, the increased production of free radicals can cause lipid peroxidation and damage proteins, mitochondria, and DNA. Mitochondrial dysfunction also increases the production of reactive species, reduces adenosine triphosphate production, and disrupts calcium homeostasis. These alterations are compounded by inflammation, glutamate excitotoxicity, and delayed apoptotic or necrotic signaling, leading to progressive damage to hair cells, synapses, and auditory neurons [24].

At inner-hair-cell synapses, excessive glutamate release may overactivate postsynaptic receptors, causing excitotoxic swelling, synaptic disconnection, and degeneration of auditory-nerve terminals. Moderate acoustic exposure may reduce ribbon synapses and afferent terminals even after temporary threshold shifts have resolved. This process, known as cochlear synaptopathy, has been proposed as one mechanism underlying "hidden hearing loss," in which individuals experience difficulty understanding speech in noise despite apparently normal pure-tone thresholds. However, such functional difficulties are not specific to synaptopathy and may also arise from other peripheral or central auditory abnormalities [25].

Direct histological confirmation of cochlear synaptic loss is not currently feasible in living humans. Extended high-frequency audiometry and otoacoustic emissions may identify early abnormalities that are not detected by conventional pure-tone audiometry [26]. Speech-in-noise testing may also reveal functional difficulties associated with apparently normal hearing thresholds.

A proteomic study of 210 workers in mining-related industries identified 46 upregulated serum proteins in participants with NIHL. The identified proteins were associated with functions such as transport, cytoskeletal organization, structural integrity, and cellular stress [27]. Although the findings suggest that systemic molecular changes accompany NIHL, they do not establish that the proteins originated from the cochlea or that they are specific biomarkers of auditory injury. Further validation is therefore required before they can be used as specific biomarkers of cochlear injury.

Cochlear injury may persist after noise exposure ends because oxidative stress, inflammation, mitochondrial dysfunction, ionic imbalance, and delayed cell death signaling may remain active [24]. This persistence creates a potential post-exposure therapeutic window during which early intervention could limit secondary injury. These mechanisms provide a biological rationale for investigating both pre-exposure protection and early post-exposure treatment. As shown in **Figure 1**, mining noise may cause both overt hair-cell injury and less apparent synaptic dysfunction. At the same time, persistent cellular damage provides the biological basis for evaluating drug-based protection as part of a comprehensive prevention strategy.

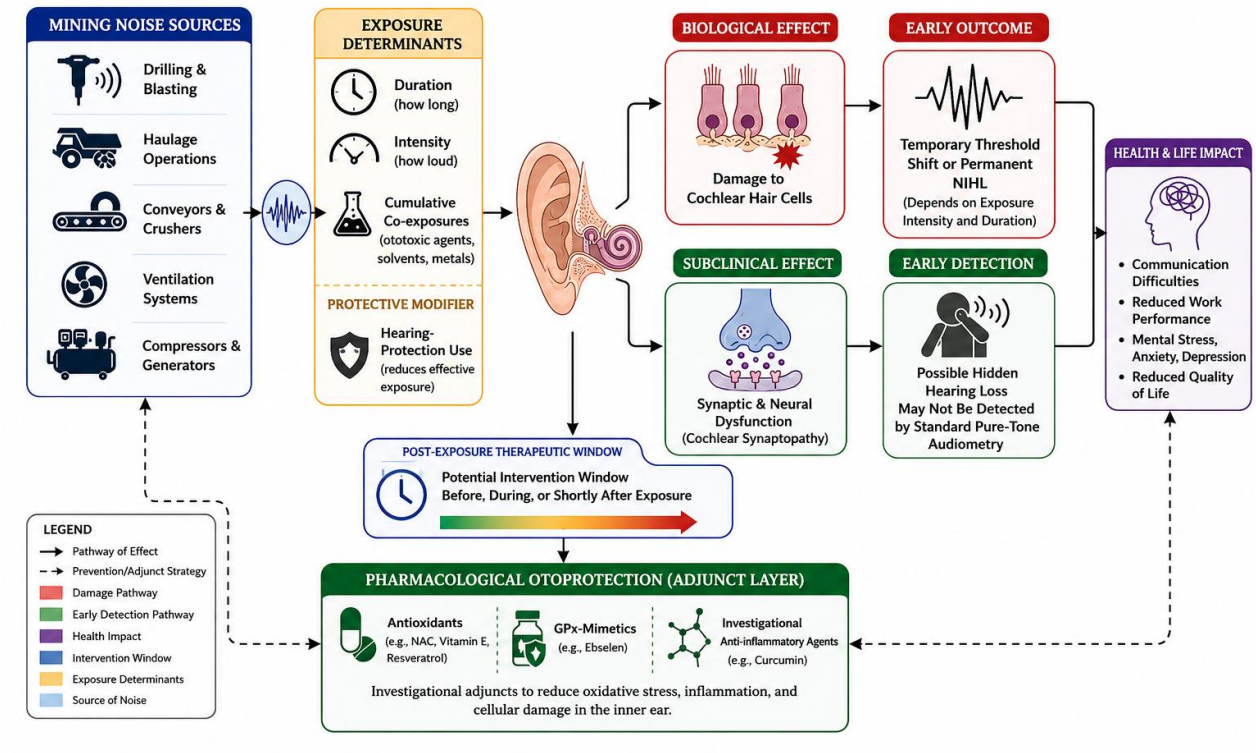

Figure 1. Pathway linking mining-related noise exposure with cochlear injury, auditory dysfunction, and wider health consequences. The figure presents major noise sources, exposure determinants, protective modifiers, hair-cell damage, cochlear synaptopathy, early auditory outcomes, the potential therapeutic window, and the proposed adjunctive role of pharmacological otoprotection.

3. CURRENT PREVENTION AND CLINICAL MANAGEMENT

Prevention of occupational noise-induced hearing loss (NIHL) in mining should follow the hierarchy of controls: elimination or substitution, engineering controls, administrative measures, and hearing protection. Exposure can be reduced through quieter equipment, automation, process redesign, machinery replacement, preventive maintenance, and noise-control requirements in mine planning [28, 29].

Engineering controls reduce noise at its source or interrupt its transmission. These measures include the installation of barriers, equipment enclosures, vibration isolation systems, damping materials, silencers, insulated cabins, remote-controlled machinery, and the separation of noisy processes. Engineering controls should be prioritized over administrative controls, which include task rotation, restricting access, limiting time spent in noisy areas, and providing quiet recovery spaces. Evidence from South African mines indicates that administrative measures and hearing protection are still used more frequently than engineering solutions that control noise at its source [29].

If exposure to hazardous noise is likely to continue, workers should wear hearing protection devices (HPDs), such as earplugs, earmuffs, or a combination of both. These devices must be appropriately selected and correctly fitted to provide effective hearing protection. Selection should consider measured noise levels, frequency characteristics, worker comfort, communication requirements, workplace conditions, and compatibility with other personal protective equipment. Manufacturer-reported attenuation ratings may overestimate the level of protection achieved under actual workplace conditions because performance is influenced by individual fit, device use, and environmental factors [30, 31]. Therefore, quantitative fit testing, correct fitting procedures, routine maintenance, worker training, and timely replacement of HPDs are essential [32].

A comprehensive hearing-conservation program should include noise assessment, engineering and administrative controls, appropriate HPD selection and fit testing, worker education, audiometric surveillance, record keeping, clinical referral, and regular program evaluation. Training should inform workers about the cumulative and permanent effects of noise exposure, the proper use of HPDs, early symptoms of hearing damage such as tinnitus and difficulty understanding speech, and the importance of promptly reporting these symptoms. Mining hearing-conservation programs may be weakened by poor coordination, limited worker participation in program planning, insufficient emphasis on engineering controls, and inadequate collaboration among relevant stakeholders [28]. These gaps are concerning because the global burden of occupational NIHL has more than doubled between 1990 and 2021 and is expected to continue rising, particularly in lower- and middle-income regions [33].

Baseline and periodic audiometry can detect changes in hearing thresholds and identify workers who need specialist assessment, but they cannot prevent cochlear injury. Results must be evaluated in conjunction with age, occupational history, job type, medication history, vibration exposure, ototoxic substances, and non-occupational noise exposure. Wearable sensors and artificial intelligence systems can also help monitor exposure and provide real-time early warnings. However, these technologies have yet to be validated under actual mining conditions and incorporated into existing hearing-conservation programs [29].

The goal of clinical management is to minimize disability and support continued participation in work. Hearing aids, assistive listening devices, communication training, quieter workstations, captioned communication, and modified duties are possible interventions. Counseling, amplification, sound therapy, and cognitive behavioral therapy are among the interventions currently supported by the strongest evidence for reducing tinnitus-related distress and may be considered for tinnitus management [34]. Patients with severe or profound hearing loss who derive limited benefit from hearing aids may be considered for cochlear implantation, particularly as the indications for this procedure have broadened in recent years [35, 36].

4. PHARMACOLOGICAL STRATEGIES FOR PREVENTION AND MITIGATION OF NOISE-INDUCED HEARING LOSS

Pharmacological strategies for noise-induced hearing loss (NIHL) aim to reduce secondary cochlear injury by targeting multiple pathological pathways as given in **Table 1** [37].

Table 1. Selected pharmacological agents investigated for prevention or mitigation of NIHL

Agent or Class	Proposed Mechanism	Evidence in Occupational/Translational Studies	Level of Evidence	Ref
N-acetylcysteine (NAC)	Glutathione precursor; restores antioxidant capacity and reduces ROS-mediated cochlear injury.	Human trials in industrial and military populations show inconsistent results. Some studies demonstrate reduced TTS, but prevention of permanent NIHL has not been confirmed.	Moderate (multiple RCTs, inconsistent outcomes)	[38-40]
D-methionine	Supports glutathione-related antioxidant pathways and reduces oxidative cochlear injury	Primarily supported by animal studies showing protection against impulse and continuous noise exposure; human occupational evidence remains insufficient.	Low (preclinical evidence)	[41]
Ebselen	GPx-mimetic antioxidant with anti-inflammatory and anti-excitotoxic activity	The Phase 2 RCT showed reduced TTS following controlled noise exposure; the long-term occupational effectiveness remains unknown.	Moderate (human RCT)	[42]
Corticosteroids	Broad suppression of inflammatory signaling and cochlear edema	May benefit acute acoustic trauma; not validated for prevention of chronic occupational NIHL	Low for prevention; moderate for acute treatment	[43]
Oridonin and plant-derived compounds	Modulation of inflammatory pathways and cellular stress responses	Protective effects demonstrated mainly in experimental noise models; no occupational human evidence	Low	[44]

4.1 Antioxidant and Metabolic Approaches

One of the most widely studied pharmacological strategies for NIHL involves the use of antioxidants. This damage includes lipid peroxidation, mitochondrial dysfunction, impairment of endogenous antioxidant systems, and hair-cell death [24]. Although several antioxidants have shown positive experimental results, they have not yet been translated into routine occupational practice due to variations in dosage, bioavailability, treatment timing, noise-exposure characteristics, and methods used to measure hearing protection [45].

In experimental models, N-acetylcysteine (NAC) has been shown to limit oxidative injury, hair-cell loss, and hearing-threshold shifts [46]. In humans, however, the findings have been inconsistent. In a prospective, double-masked, crossover study, oral NAC administered at 1,200 mg daily for 14 days reduced temporary high-frequency threshold shifts in 53 noise-exposed male workers. The observed effect also appeared to be influenced by glutathione S-transferase genotype [40]. However, a randomized, double-masked, placebo-controlled study involving 566 military personnel failed to demonstrate an overall benefit for the primary outcome measure, standard threshold shift following weapons training, although some secondary analyses indicated a potential benefit [39]. In addition, a systematic review of randomized controlled trials found no overall protective effect [38]. These inconsistent findings likely reflect substantial heterogeneity in NAC dosage, treatment duration, and timing of administration, noise-exposure conditions, genetic susceptibility, and the audiometric criteria used to define hearing-threshold changes. Consequently, the optimal dosing regimen, appropriate target population, and clinical value of long-term

prophylactic use remain unclear. Nevertheless, NAC appears to have an acceptable safety profile when used over short treatment periods.

Ebselen has also been shown to be effective in controlled human studies. In a randomized phase 2 trial, a dose of 400 mg twice daily reduced temporary threshold shift at 4 kHz following controlled sound exposure, whereas lower and higher doses did not show the same benefit [47]. However, the study assessed temporary rather than permanent hearing loss and cannot be directly extrapolated to recurrent, long-term mining exposure.

D-methionine has shown protective effects in experimental models, particularly when administered before noise exposure [41]. Some animal research has also investigated early post-exposure administration. Still, human evidence remains insufficient to establish clinical efficacy, optimal dosing, treatment duration, or long-term safety during repeated occupational exposure [24, 48, 49]. Other antioxidant and metabolic approaches include alpha-lipoic acid, vitamins C and E, magnesium, coenzyme Q10, and glutathione-related compounds. Some experimental and small human studies suggest reductions in oxidative damage or temporary changes in hearing thresholds. However, limited sample sizes, short follow-up periods, variable formulations, and poor inner-ear bioavailability prevent firm conclusions about their ability to prevent permanent occupational NIHL [7, 46].

Resveratrol has antioxidant, anti-inflammatory, and anti-apoptotic properties and has reduced hearing impairment and cochlear injury in animal models. However, its clinical relevance remains limited by the absence of convincing human evidence [50].

4.2 Anti-Inflammatory, Anti-Excitotoxic, and Cell-Survival Therapies

Inflammatory, excitotoxic, and cell-death pathways also represent potential therapeutic targets in NIHL. Corticosteroids may benefit some patients with acute acoustic trauma by reducing cochlear inflammation and edema. However, their uncertain preventive efficacy and potential systemic adverse effects limit their suitability for repeated occupational use [43].

More selective agents targeting tumor necrosis factor, interleukin-1, cyclooxygenase-2, p38 signaling, and nuclear factor-kappa B have produced protective effects in experimental models. Nevertheless, inflammation may contribute to both cochlear injury and tissue repair, meaning that prolonged suppression could interfere with recovery [45, 49].

Agents targeting glutamate receptors, calcium overload, c-Jun N-terminal kinase, caspases, and Bcl-2-family signaling have also reduced synaptic and hair-cell injury in animal models. Clinical translation remains limited by narrow therapeutic windows, systemic adverse effects, and the involvement of multiple overlapping cell death mechanisms [45, 46].

Neurotrophic agents, ferroptosis inhibitors, autophagy modulators, regenerative therapies, and other plant-derived compounds remain at an early experimental stage. Although several have reduced synaptic or cellular injury in preclinical models, limited human evidence, uncertain long-term safety, and narrow therapeutic windows remain major barriers to clinical translation [51].

4.3 Human Evidence and Current Clinical Position

Pharmacological prevention of noise-induced hearing loss has been investigated in humans using a variety of interventions, including anti-inflammatory compounds, metabolic agents, and antioxidants. Among these interventions, ebselen has demonstrated one of the more consistent signals of benefit in controlled human studies; however, its effects have been limited mainly to temporary hearing changes rather than long-term hearing preservation. In general, evidence for most pharmacological interventions remains inconsistent because of variations in study populations, noise exposure conditions, treatment timing, dosage regimens, and outcome assessment methods [7, 42].

The clinical relevance of pharmacological therapy depends largely on the timing of administration and characteristics of occupational exposure. In mining environments, pre-exposure prophylaxis may require repeated dosing, sustained adherence, and long-term safety monitoring; therefore, it may be more feasible when hazardous noise exposure is predictable. Findings from acute acoustic trauma studies, including corticosteroid-based approaches, cannot be directly translated to repeated workplace exposure, which results in the gradual development of occupational NIHL [43].

At present, no pharmacological treatment has been shown to reverse established NIHL, regenerate human cochlear hair cells, or repair extensive cochlear synaptic damage [37]. Future clinical trials should prioritize clinically meaningful outcomes, including permanent threshold shifts, speech-in-noise performance, tinnitus severity, functional communication, and long-term safety, rather than relying primarily on temporary threshold shifts. Pharmacological therapy is still investigational and should not replace exposure control, hearing protection, audiological surveillance, or rehabilitation.

5. TRANSLATIONAL CHALLENGES, DRUG DELIVERY, AND FUTURE DIRECTIONS

5.1 Drug Delivery and Safety

Pharmacological prevention of noise-induced hearing loss (NIHL) needs therapeutic agents to be delivered to the cochlea during a biologically relevant treatment window. The most convenient method in the workplace is systemic administration, especially orally. But factors such as absorption, metabolism, bioavailability, treatment adherence, and inter-individual differences may affect its effectiveness. The limitations are particularly relevant to the mining industry, where people might be continuously exposed to noise for many years and therefore need long-term preventive measures. Intratympanic administration is an invasive technique requiring clinical intervention. It can achieve higher drug levels in the cochlea but is not practical for regular or repeated prophylactic use to lower the risk of noise-induced hearing loss in miners. New delivery systems, such as nanoparticles, liposomes, and hydrogel formulations, could improve drug targeting to the cochlea, increase drug stability, and enable more gradual drug release. However, their long-term safety, manufacturability, and clinical applicability remain uncertain [51-53].

Long-term safety is a large concern before pharmacological interventions can be incorporated into workplace hearing-conservation programs. For mining purposes, these interventions would probably need to be repeated over long periods rather than be short-term treatments. Hence, the potential adverse effects on the liver, kidneys, cardiovascular system, and brain, as well as potential drug interactions, should be carefully weighed against the potential benefits of hearing preservation [42, 49].

5.2 Integration into Mine Hearing-Conservation Programs

Pharmacological interventions would be incorporated into mining practice if there were clearly defined protocols for dosage regimens, worker eligibility, medical screening, adherence monitoring, adverse event reporting, and occupational exposure documentation. Accurate data on workplace noise exposure, work tasks, hearing protection measures, and individual factors would also be required to assess treatment efficacy. This is followed, where appropriate, by engineering controls, administrative controls, exposure monitoring, audiological surveillance, and effective hearing-protection programs, as shown in Figure 2, which presents the hearing-loss prevention hierarchy of controls.

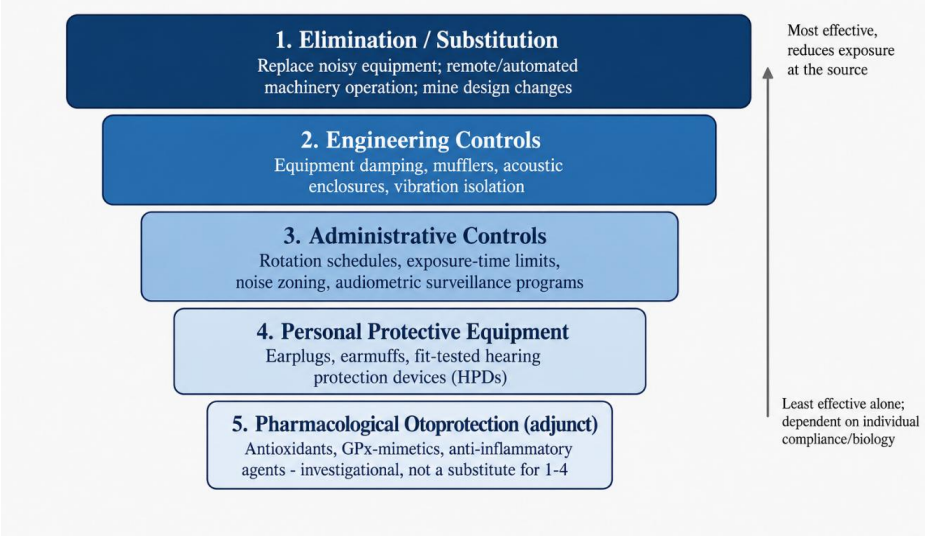

Figure 2. Hierarchy of occupational controls for mining-related NIHL prevention, illustrating pharmacological otoprotection as a complementary rather than replacement strategy.

The potential protective effects of pharmacological interventions must be interpreted carefully because observed improvements may result from the drug intervention itself, concurrent improvements in workplace controls, or changes in hearing-

conservation practices. Therefore, controlled occupational trials are required to distinguish the specific contribution of pharmacological interventions from other preventive measures [29].

5.3 Emerging Biomarkers for Early Detection of Cochlear Injury

Early detection of noise-induced cochlear injury remains a major challenge in occupational hearing conservation. Conventional pure-tone audiometry may not detect early neural or synaptic damage. Other assessments, including auditory brainstem responses, speech-in-noise testing, otoacoustic emissions, extended high-frequency audiometry, and molecular biomarkers, are therefore receiving increasing attention. These methods may help identify cochlear changes that occur before clinically significant hearing loss becomes evident.

However, no currently available biomarker provides a validated and specific diagnosis of cochlear synaptopathy, particularly for large-scale occupational screening. Further validation in mining populations is therefore required before these approaches can be incorporated into routine hearing-conservation programs [54, 55].

5.4 Gene-Based and Regenerative Therapeutic Approaches

Advances in molecular biology have increased interest in gene-based, neurotrophin-mediated, and regenerative approaches to NIHL. Experimental strategies targeting synaptic repair, cell-survival pathways, and cochlear regeneration have shown promising results in preclinical models. These strategies include gene delivery, neurotrophic factor use, and approaches to restoring damaged cochlear structures. However, their translation into occupational medicine remains challenging due to limitations in delivery efficiency, immune responses, off-target effects, treatment timing, and uncertain long-term safety profiles [56, 57].

6. FUTURE RESEARCH

Future studies should move beyond short-term measures of temporary threshold shift and assess clinically relevant outcomes, including permanent threshold shifts, speech-in-noise perception, tinnitus severity, auditory nerve function, long-term safety, treatment adherence, and cost-effectiveness. During clinical trials conducted in mining populations, attention should be given to the level and duration of noise exposure, the type of work activity, the use of hearing protection devices, and possible co-exposure to other ototoxic agents. This information is crucial for making the study's findings more applicable and translatable to real-world work environments. More personalized approaches to NIHL prevention will require implementing standardized trial designs, incorporating new NIHL biomarkers, and identifying workers most likely to respond to NIHL prevention efforts. Pharmacological, gene-based, and regenerative therapies remain experimental and are not routinely used in occupational settings. These methods should be used in addition to, not instead of, an integrated hearing-conservation program.

7. CONCLUSION

Noise-induced hearing loss is a significant but largely preventable occupational health issue among miners. It results from repeated exposure to hazardous noise, inadequate hearing-conservation measures, co-exposure to chemical and physical hazards, and individual susceptibility factors. Antioxidants, metabolic agents, corticosteroids, anti-inflammatory drugs, synaptic repair agents, and advanced drug-delivery systems have demonstrated promising experimental outcomes; however, only a limited number of human proof-of-concept studies have been conducted, and the reported findings remain inconsistent.

The current lack of well-designed clinical trials specifically targeting miners, together with uncertainties regarding optimal dosage, drug-delivery challenges, and long-term safety, limits the potential for widespread occupational application. Therefore, pharmacological therapies should be regarded as investigational supportive approaches rather than substitutes for established hearing-conservation strategies, including noise exposure control, hearing protection, audiological surveillance, and rehabilitation.

ACKNOWLEDGEMENTS

The authors extend their appreciation to Northern Border University, Saudi Arabia, for supporting this work through project number (NBU-CRP-2026-2042).

FUNDING

None.

AUTHOR CONTRIBUTIONS

Abida Khan: Conceptualization, Data collection, Critical Analysis, Manuscript drafting, and Review and editing.

Howayada Mahany Mostafa: Data collection, Manuscript drafting, Critical Analysis, and Review and editing

Syed Raziuddin Quadri: Data collection, Manuscript drafting, Review and editing.

Mohd Imran: Conceptualization, Supervision, Critical Analysis, Review, and editing.

All authors approved the final version and accept accountability for the work

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used OpenAI ChatGPT (GPT-5.6 Thinking) to assist with language refinement, grammatical correction, improvement of textual flow, manuscript organization, formatting, and verification of bibliographic information. The tool was not used to generate, alter, or fabricate the scientific data, study findings, or conclusions presented in this review. All AI-assisted content was critically reviewed, verified, and revised by the authors.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ETHICS STATEMENT

Ethical approval was not required for this study.

DATA AVAILABILITY STATEMENT

Data supporting the findings of this study are available in the cited references.

REFERENCES

[1] Natarajan N, Batts S, Stankovic KM. Noise-Induced Hearing Loss. Journal of Clinical Medicine. 2023;12(6):2347. doi:10.3390/jcm12062347.

[2] Chen KT, Su SB. A review of occupational noise-induced hearing loss: focus on mechanisms and preventive measures. Br Med Bull. 2025;156(1). doi:10.1093/bmb/ldaf020.

[3] Chen KH, Su SB, Chen KT. An overview of occupational noise-induced hearing loss among workers: epidemiology, pathogenesis, and preventive measures. Environ Health Prev Med. 2020;25(1):65. doi:10.1186/s12199-020-00906-0.

[4] Wei X, Yang J, Zheng J, Chen H. Meta-analysis of Occupational Factors Contributing to Variability in Noise-induced Hearing Loss Severity. Noise Health. 2026;28(130):24-32. doi:10.4103/nah.nah_167_25.

[5] Cudjoe FA, Opoku DA, Ayisi-Boateng NK, Osarfo J, Boateng KS, Sackey LNA, et al. Health effects of occupational noise exposure on heavy-duty equipment operators and exposed workers in a mining firm in Ghana. PLOS ONE. 2025;20(9):e0332600. doi:10.1371/journal.pone.0332600.

[6] Moroe N, Khoza-Shangase K, Kanji A, Ntlhakana L. The management of occupational noise-induced hearing loss in the mining sector in Africa: A systematic review—1994 to 2016. Noise & Vibration Worldwide. 2018;49(5):181-90. doi:10.1177/0957456518781860.

[7] Gupta A, Koochakzadeh S, Nguyen SA, Brennan EA, Meyer TA, Lambert PR. Pharmacological Prevention of Noise-induced Hearing Loss: A Systematic Review. Otol Neurotol. 2021;42(1):2-9. doi:10.1097/MAO.0000000000002858.

[8] Padhan S, Goswami S, Pradhan S, Singh UK, Mishra M, Guria R. Mapping the global landscape of occupational noise hazards (ONH) in the mining industry: A systematic and metadata-driven review. Archives of Environmental & Occupational Health. 2026:1-19. doi:10.1080/19338244.2026.2681723.

[9] Wang X, Kang N, Liu K, Ning K, Dong Y, Ye M. [Application of four risk assessment methods to risk assessment of noise-induced hearing loss in metal mining enterprises]. Wei Sheng Yan Jiu. 2025;54(2):301-9. doi:10.19813/j.cnki.weishengyanjiu.2025.02.019.

[10] Camargo HE, Azman AS, Alcorn L. Development of noise controls for longwall shearer cutting drums. Noise Control Engineering Journal. 2016;64(5):573. doi:10.3397/1/376402.

[11] Peterson JS. Experimental methods to reduce noise generated by haul trucks and LHDs. Noise Control Eng J. 2018;66(5):446-58. doi:10.3397/1/376638.
[12] Themann CL, Masterson EA. Occupational noise exposure: A review of its effects, epidemiology, and impact with recommendations for reducing its burden. J Acoust Soc Am. 2019;146(5):3879. doi:10.1121/1.5134465.
[13] Tank ND, Rupani MP, Shah IA, Dhatrak SV. Prevalence and predictors of high-frequency hearing loss among mine workers in Gujarat, western India: a cross-sectional study on the need to implement a comprehensive hearing conservation program. Int Arch Occup Environ Health. 2024;97(4):365-75. doi:10.1007/s00420-024-02050-6.
[14] Lawson SM, Masterson EA, Azman AS. Prevalence of hearing loss among noise-exposed workers within the Mining and Oil and Gas Extraction sectors, 2006-2015. Am J Ind Med. 2019;62(10):826-37. doi:10.1002/ajim.23031.
[15] Akbar K, Ma'rufi I, Surach A, Sela C, Sujoso A, Hartanti R, et al. Occupational hearing impairment in coal mining across Asia-Pacific: Patterns, risks, and implications. Journal of Occupational and Environmental Hygiene. 2026;23(4):237-246. doi:10.1080/15459624.2025.2589135.
[16] Kanji A, Khoza-Shangase K, Ntlhakana L. Noise-induced hearing loss: what South African mineworkers know. Int J Occup Saf Ergon. 2019;25(2):305-10. doi:10.1080/10803548.2017.1412122.
[17] Naicker K. Noise-induced hearing loss and hearing protection: Attitudes at a South African coal mine. S Afr J Commun Disord. 2024;71(1):e1-e12. doi:10.4102/sajcd.v71i1.966.
[18] Zhou J, Shi Z, Zhou L, Hu Y, Zhang M. Occupational noise-induced hearing loss in China: a systematic review and meta-analysis. BMJ Open. 2020;10(9):e039576. doi:10.1136/bmjopen-2020-039576.
[19] Pillay M. Chemicals, noise and occupational hearing health in South Africa: A mapping study. S Afr J Commun Disord. 2020;67(2):e1-e11. doi:10.4102/sajcd.v67i2.693.
[20] Khoza-Shangase K. The Association Between HIV/AIDS, Ototoxicity of Its Treatments, and Occupational Noise Induced Hearing Loss: A Narrative Review Mapping the Existing Literature and Identifying Research Gaps. Int J Environ Res Public Health. 2025;22(4). doi:10.3390/ijerph22040487.
[21] Sułkowski W, Owczarek K, Olszewski J. Contemporary noise-induced hearing loss (NIHL) prevention. Otolaryngologia Polska. 2017;71:1-7. doi:10.5604/01.3001.0010.2241.
[22] Shkembi A, Smith LM, Bregg S, Neitzel RL. Evaluating Occupational Noise Exposure as a Contributor to Injury Risk among Miners. Ann Work Expo Health. 2022;66(9):1151-61. doi:10.1093/annweh/wxac059.
[23] Jain RK, Pingle SK, Tumane RG, Thakkar LR, Jawade AA, Barapatre A, et al. Cochlear Proteins Associated with Noise-induced Hearing Loss: An Update. Indian J Occup Environ Med. 2018;22(2):60-73. doi:10.4103/ijoem.IJOEM_43_18.
[24] Pisani A, Paciello F, Montuoro R, Rolesi R, Galli J, Fetoni AR. Antioxidant Therapy as an Effective Strategy against Noise-Induced Hearing Loss: From Experimental Models to Clinic. Life (Basel). 2023;13(4). doi:10.3390/life13041035.
[25] Wei M, Wang W, Liu Y, Mao X, Chen TS, Lin P. Protection of Cochlear Ribbon Synapses and Prevention of Hidden Hearing Loss. Neural Plasticity. 2020;2020(1):8815990. doi:10.1155/2020/8815990.
[26] Preobrazhenskaya E, Sukhova A, Il'nitskaya A, Zor'kina L. Comparative evaluation of diagnostic sensitivity of contemporary audiometry methods in occupations exposed to noise. Meditsina Truda i Promyshlennaia Ekologiia. 2017(2):38-42.
[27] Tumane RG, Thakkar L, Pingle SK, Jain RK, Jawade AA, Raje DV. Expression of serum proteins in noise induced hearing loss workers of mining based industry. J Proteomics. 2021;240:104185. doi:10.1016/j.jprot.2021.104185.
[28] Moroe N, Khoza-Shangase K. Stakeholder perspectives on hearing conservation programmes in the South African mining sector: A qualitative study. Health Research Policy and Systems. 2025;23(1):55. doi:10.1186/s12961-025-01326-8.
[29] Madahana MCI, Ekoru JED, Sebothoma B, Khoza-Shangase K. Development of an artificial intelligence based occupational noise induced hearing loss early warning system for mine workers. Front Neurosci. 2024;18:1321357. doi:10.3389/fnins.2024.1321357.
[30] Karch SJ, Federman J, Ginsberg JT, Qureshi I. Measuring earplug noise attenuation: A comparison of laboratory and field methods. J Occup Environ Hyg. 2024;21(1):68-76. doi:10.1080/15459624.2023.2268190.
[31] Hayes M, Hammond S, Montgomery A, Stephenson L. Improving Hearing Protection Device Noise Attenuation Through Fit-Testing in an Occupational Health Clinic. Workplace Health & Safety. 2022;70:216507992110679. doi:10.1177/21650799211067927.

[32] Morata TC, Gong W, Tikka C, Samelli AG, Verbeek JH. Hearing protection field attenuation estimation systems and associated training for reducing workers' exposure to noise. Cochrane Database Syst Rev. 2024;5(5):CD015066. doi:10.1002/14651858.CD015066.pub2.
[33] Gong X, Yi M, Jiang C, Xiong Q, Xu B, Weng F, et al. Global burden and trends of occupational noise-induced hearing loss (1990–2021) and projection to 2040. Frontiers in Public Health. 2025;13. doi:10.3389/fpubh.2025.1682413.
[34] Sherlock L, Ballard-Hernandez J, Boudin-George A, Clark K, Colandrea M, Edmonds C, et al. Clinical Practice Guideline for Management of Tinnitus: Recommendations From the US VA/DOD Clinical Practice Guideline Work Group. JAMA Otolaryngology–Head & Neck Surgery. 2025;151:513-20. doi:10.1001/jamaoto.2025.0052.
[35] Zeitler DM, Prentiss SM, Sydlowski SA, Dunn CC. American Cochlear Implant Alliance Task Force: Recommendations for Determining Cochlear Implant Candidacy in Adults. Laryngoscope. 2024;134 Suppl 3(Suppl 3):S1-S14. doi:10.1002/lary.30879.
[36] Shen S, Sayyid Z, Andresen N, Carver C, Dunham R, Marsiglia D, et al. Longitudinal Auditory Benefit for Elderly Patients After Cochlear Implant for Bilateral Hearing Loss, Including Those Meeting Expanded Centers for Medicare & Medicaid Services Criteria. Otol Neurotol. 2023;44(9):866-72. doi:10.1097/MAO.0000000000003983.
[37] Kitama T, Nishiyama T, Hosoya M, Shimanuki MN, Ueno M, You F, et al. Noise-Induced Hearing Loss: Overview and Future Prospects for Research on Oxidative Stress. Int J Mol Sci. 2025;26(10). doi:10.3390/ijms26104927.
[38] Chang PH, Liu CW, Hung SH, Kang YN. Effect of N-acetyl-cysteine in prevention of noise-induced hearing loss: a systematic review and meta-analysis of randomized controlled trials. Arch Med Sci. 2022;18(6):1535-41. doi:10.5114/aoms/109126.
[39] Kopke R, Slade MD, Jackson R, Hammill T, Fausti S, Lonsbury-Martin B, et al. Efficacy and safety of N-acetylcysteine in prevention of noise induced hearing loss: a randomized clinical trial. Hear Res. 2015;323:40-50. doi:10.1016/j.heares.2015.01.002.
[40] Lin CY, Wu JL, Shih TS, Tsai PJ, Sun YM, Ma MC, et al. N-Acetyl-cysteine against noise-induced temporary threshold shift in male workers. Hearing Research. 2010;269:42-7. doi:10.1016/j.heares.2010.07.005.
[41] Campbell K, Cosenza N, Meech R, Buhnerkempe M, Qin J, Rybak L, et al. Preloaded D-methionine protects from steady state and impulse noise-induced hearing loss and induces long-term cochlear and endogenous antioxidant effects. PLoS One. 2021;16(12):e0261049. doi:10.1371/journal.pone.0261049.
[42] Kil J, Harruff EE, Longenecker RJ. Development of ebselen for the treatment of sensorineural hearing loss and tinnitus. Hear Res. 2022;413:108209. doi:10.1016/j.heares.2021.108209.
[43] Zloczower E, Tsur N, Hershkovich S, Fink NMT. Efficacy of Oral Steroids for Acute Acoustic Trauma. Audiology and Neurotology. 2022;27:312-20. doi:10.1159/000522051.
[44] Chen MB, Li MH, Wu LY, Wang R, Long X, Zhang L, et al. Oridonin employs interleukin 1 receptor type 2 to treat noise-induced hearing loss by blocking inner ear inflammation. Biochem Pharmacol. 2023;210:115457. doi:10.1016/j.bcp.2023.115457.
[45] Xu K, Xu B, Gu J, Wang X, Yu D, Chen Y. Intrinsic mechanism and pharmacologic treatments of noise-induced hearing loss. Theranostics. 2023;13(11):3524-49. doi:10.7150/thno.83383.
[46] Le Prell CG. Prevention of Noise-Induced Hearing Loss Using Investigational Medicines for the Inner Ear: Previous Trial Outcomes Should Inform Future Trial Design. Antioxid Redox Signal. 2022;36(16-18):1171-202. doi:10.1089/ars.2021.0166.
[47] Kil J, Lobarinas E, Spankovich C, Griffiths SK, Antonelli PJ, Lynch ED, et al. Safety and efficacy of ebselen for the prevention of noise-induced hearing loss: a randomised, double-blind, placebo-controlled, phase 2 trial. Lancet. 2017;390(10098):969-79. doi:10.1016/S0140-6736(17)31791-9.
[48] Deng Z, Lin F, Zhou L, Wang S, Li J, He L. Drug-Therapeutic Strategies for Noise-Induced Hearing Loss: A Narrative Review. Noise Health. 2025;27(126):203-9. doi:10.4103/nah.nah_187_24.
[49] Santaolalla Sanchez FJ, Gutierrez Posso JD, Santaolalla Montoya F, Zabala JA, Arrizabalaga-Iriondo A, Revuelta M, et al. Pathogenesis and New Pharmacological Approaches to Noise-Induced Hearing Loss: A Systematic Review. Antioxidants (Basel). 2024;13(9). doi:10.3390/antiox13091105.
[50] Liu YH, Jiang YH, Li CC, Chen XM, Huang LG, Zhang M, et al. Involvement of the SIRT1/PGC-1α Signaling Pathway in Noise-Induced Hidden Hearing Loss. Frontiers in Physiology. 2022;13:798395. doi:10.3389/fphys.2022.798395.

[51] Jimoh OO, Ajuwon T, Okonkwo SS, Awoyemi RF, Olaosebikan I, Olahanmi OA, et al. PLGA nanoparticles in otoprotection and inner ear regeneration: a new frontier in nanomedicine for hearing disorders. RSC Adv. 2026;16(1):76-106. doi:10.1039/D5RA06007A.
[52] Thakur NS, Rus I, Sparks E, Agrahari V. Dual stimuli-responsive and sustained drug delivery NanoSensoGel formulation for prevention of cisplatin-induced ototoxicity. J Control Release. 2024;368:66-83. doi:10.1016/j.jconrel.2024.02.005.
[53] Zhang H, Xu D, Wang H, Chai R, Zhao Y. Cutting-Edge Achievements of Inner Ear Drug Delivery Systems. Advanced NanoBiomed Research. 2024;4(6):2400004. doi:10.1002/anbr.202400004.
[54] Wang H, Aiken SJ, Wang J. Consequences and Mechanisms of Noise-Induced Cochlear Synaptopathy and Hidden Hearing Loss, With Focuses on Signal Perception in Noise and Temporal Processing. Adv Sci (Weinh). 2025;12(29):e2409322. doi:10.1002/advs.202409322.
[55] Yaşar M, Öner F, Atalay F, Anbar SS. Cochlear Synaptopathy Evaluation With Electrocochleography in Patients With Hearing Difficulty in Noise Despite Normal Hearing Levels. Clin Otolaryngol. 2025;50(1):75-81. doi:10.1111/coa.14235.
[56] Yilmaz NK, Ozen D, da Costa Monsanto R, Ocak E, Schuster AK, Shimura T, et al. Efficiency of gene therapy for sensorineural hearing loss in mouse model: A meta-analysis. Laryngoscope Investig Otolaryngol. 2024;9(6):e70048. doi:10.1002/lio2.70048.
[57] Zeng FG, Qi J, Wu CC, Shu Y, Chai R. Treating Hearing Loss: From Cochlear Implantation to Gene Therapy. Adv Sci (Weinh). 2025;12(41):e09960. doi:10.1002/advs.202509960.