

# Technology-driven approaches to occupational noise-induced hearing loss management and hearing conservation programmes in Africa

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## ABSTRACT

**Background:** Occupational noise-induced hearing loss (ONIHL) is a major public health concern in Africa, particularly in high-risk industries such as mining, manufacturing, and construction. While hearing conservation programmes (HCPs) exist, their effectiveness is often limited by poor enforcement, inadequate infrastructure, and low adoption of emerging technologies. Advancements in fourth industrial revolution (4IR) technologies – such as artificial intelligence (AI), tele-audiology, mobile health (mHealth), and the internet of things (IoT) – offer new opportunities for ONIHL prevention. However, their integration into occupational hearing healthcare in Africa remains limited.

**Objective:** To explore technology-driven approaches to ONIHL management and HCPs in Africa, highlighting advancements, barriers, and opportunities for integrating digital solutions into occupational health frameworks.

**Methods:** For this narrative review, PubMed, Scopus, Web of Science, ScienceDirect, Google Scholar, and African Journals Online (AJOL) were searched for relevant articles. The selected studies were categorised as highly or moderately relevant. Thematic analysis was conducted to synthesise key findings on AI-driven audiology, tele-audiology and mHealth, IoT-integrated hearing conservation, and regulatory challenges.

**Results:** A total of 1 147 publications were identified, of which 55 were evaluated for relevance; 22 were included in the review. Ten were considered to be highly relevant and 12 to be moderately relevant. AI-based solutions show promise for early detection and predictive analytics in ONIHL management, but face barriers such as high costs and limited digital infrastructure. Tele-audiology and mHealth interventions can improve access to hearing healthcare in underserved areas, yet connectivity and data security challenges persist. IoT-enabled hearing protection devices enhance real-time noise monitoring, but remain underutilised due to high costs and policy gaps. Moderately relevant studies further highlight implementation barriers, including reliance on paper-based systems, low digital literacy, and limited funding for technological innovation. Weak regulatory enforcement further limits technology adoption in HCPs.

**Conclusion:** While 4IR technologies present significant opportunities for ONIHL prevention, their implementation in Africa requires investment, regulatory reform, and multi-sectoral collaboration. Policy updates, financial incentives, and workforce training are crucial to integrating these innovations into occupational health strategies. The African experience offers lessons for other low- and middle-income countries, and future research should prioritise examining real-world industry adoption of these technologies.

## INTRODUCTION

Occupational noise-induced hearing loss (ONIHL) remains one of the most prevalent, yet preventable, occupational diseases worldwide,<sup>1</sup> particularly in low- and middle-income countries (LMICs), where regulatory enforcement and occupational health infrastructure are often inadequate.<sup>2</sup> In Africa, industrialisation, mining, construction, and manufacturing industries expose workers to hazardous noise levels,<sup>3</sup> contributing significantly to the burden of ONIHL. While traditional hearing conservation programmes (HCPs) have been implemented in some sectors, their effectiveness is often limited by resource constraints, poor adherence, and a lack of integration with emerging digital health solutions.<sup>4,5</sup> With advancements in technology – particularly in artificial intelligence (AI), tele-audiology, internet of things (IoT), and digital health – there is an opportunity to revolutionise the management and prevention of ONIHL in Africa.

The burden of ONIHL in Africa is exacerbated by socio-economic and structural challenges.<sup>6</sup> High-risk sectors such as mining, manufacturing, and agriculture employ a large proportion of the workforce

under suboptimal occupational health and safety (OHS) conditions.<sup>7</sup> Inadequate regulation and enforcement, coupled with limited access to preventive audiology services, contribute to delayed diagnosis and management of ONIHL.<sup>8,9</sup> Additionally, many African workers lack awareness of the risks associated with occupational noise exposure and often do not prioritise hearing protection, given more immediate occupational hazards such as respiratory diseases and physical injuries.<sup>10</sup>

In South Africa, the mining industry – a major contributor to the economy – has one of the highest rates of ONIHL, with studies indicating that, despite existing HCPs, many workers develop hearing loss due to inconsistent use of hearing protection devices (HPDs), limited audiometric surveillance, and poor noise monitoring practices.<sup>11,12</sup> Similar trends are observed in Nigeria's sawmill industry, where excessive noise exposure occurs with minimal protective measures.<sup>13</sup> This issue is not unique to southern or South Africa. Many LMICs struggle with ineffective enforcement of hearing conservation protocols, as seen in studies from Malaysia

and India.<sup>14,15</sup> These recurring patterns of poor enforcement of regulations, inadequate use of protective technologies, and limited surveillance highlight the systemic nature of ONIHL risks in resource-constrained settings, and underscore the urgent need for enhanced technological interventions to strengthen HCPs across African workplaces.

The fourth industrial revolution (4IR) ushered in an era of digital transformation that presents opportunities to enhance OHS measures.<sup>16</sup> Technological advancements can address limitations of conventional HCPs by improving early detection, facilitating continuous monitoring, and promoting individualised hearing conservation strategies.<sup>17</sup>

First, as far as AI and predictive analytics are concerned, AI-driven solutions can improve early diagnosis of ONIHL, by analysing large datasets from audiometric testing and occupational noise exposure levels, and individual risk factors, to predict ONIHL progression.<sup>18</sup> Artificial Intelligence algorithms have demonstrated the potential to automate hearing screenings, reducing dependence on specialist audiologists and improving accessibility in resource-limited settings.<sup>17</sup> Artificial intelligence can also support occupational noise management by identifying high-risk workers and recommending tailored interventions.<sup>19</sup>

Second, in terms of tele-audiology and mHealth solutions, the use of tele-audiology has been shown to expand access to hearing healthcare in LMICs by enabling remote hearing assessments and consultations.<sup>20</sup> Smartphone-based audiometry and digital hearing health platforms can facilitate large-scale hearing screenings, particularly in rural and underserved areas.<sup>21</sup> Telehealth solutions also enable ongoing worker education, reinforcing compliance with HCP protocols.<sup>22</sup>

Third, with regard to IoT and wearable hearing protection devices, IoT-integrated HPDs provide real-time monitoring of noise exposure, alerting workers and supervisors when sound levels exceed safe thresholds.<sup>23</sup> These smart HPDs can also record and analyse exposure data, contributing to improved occupational risk assessments and governance compliance.<sup>24</sup>

Last, when it comes to big data and noise management strategies, the application of big data analytics in occupational health enables the identification of noise exposure patterns across industries, facilitating data-driven policymaking.<sup>25</sup> Noise mapping tools and environmental sensors can improve workplace noise control strategies, ensuring that interventions are both proactive and effective.<sup>26</sup>

While technological innovations offer promising solutions, their successful implementation in Africa requires a contextually responsive approach. Challenges such as digital infrastructure gaps, workforce digital literacy, and financial constraints must be addressed to ensure equitable access to technology-driven ONIHL interventions.<sup>27</sup> Moreover, ethical considerations regarding data privacy, informed consent, and algorithmic bias in AI-driven solutions must be examined critically to align with occupational health best practices.<sup>28,29</sup>

Given Africa's diverse economic and industrial landscapes, a one-size-fits-all approach to ONIHL prevention may not be effective. Traditional HCPs often rely on outdated, resource-intensive methods that do not address the increasing burden of occupational

noise exposure.<sup>2,30</sup> The integration of digital solutions offers the potential to overcome these challenges, yet adoption remains slow due to limited policy enforcement and industry hesitancy.<sup>2</sup> By understanding the barriers and opportunities in this transition, stakeholders can develop more sustainable, culturally appropriate, scalable, and effective interventions, which require collaboration – engaging governments, industries, healthcare providers, and worker unions.<sup>31</sup>

Advancements in technology-driven interventions present an opportunity to rethink and modernise occupational hearing conservation strategies in Africa. However, their feasibility and implementation remain uncertain, necessitating a critical review of existing literature to assess both the potential benefits and limitations of these innovations.

The aim of this narrative review was to explore and synthesise the available literature on technology-driven approaches to ONIHL prevention and HCPs in Africa and other LMICs. Specifically, it sought to:

- Examine the burden of ONIHL in Africa, highlighting industry-specific risks and challenges
- Identify and analyse technological advancements in ONIHL management, including AI, tele-audiology, IoT, and big data analytics
- Evaluate the feasibility, accessibility, and effectiveness of these technologies within the African occupational health context
- Identify potential barriers and facilitators to the adoption of technology-driven solutions for ONIHL management
- Provide recommendations for policymakers, industry stakeholders, and healthcare professionals on integrating 4IR technologies into sustainable and contextually relevant HCPs in Africa

By consolidating evidence from existing research, this review contributes to the discourse on digital transformation in occupational hearing conservation, offering insights into how Africa can leverage 4IR technologies to mitigate the impact of ONIHL. This review offers not only a synthesis of technological innovations in ONIHL prevention, but also a focused lens on their relevance and feasibility in African occupational settings – something that previous reviews have not fully explored. Earlier global reviews have generally emphasised broad technological trends without adequately addressing the contextual factors that influence their adoption in LMICs. By anchoring the discussion in Africa-specific challenges, such as regulatory inertia, infrastructure deficits, and industry-level implementation barriers, this review provides a critical framework for translating global advancements into actionable strategies within under-resourced occupational health systems. In this way, the review fills an important gap between global innovation discourse and regional implementation realities.

## METHODS

A narrative review was chosen to synthesise diverse sources of literature, identify knowledge gaps, and provide a broad, contextualised understanding of how 4IR technologies – including AI, tele-audiology, IoT, mHealth, and big data analytics – can enhance ONIHL prevention and hearing conservation efforts. Findings from peer-reviewed journal articles, policy documents, government reports, and grey literature were integrated to provide a comprehensive examination of the technological advances in occupational audiology.

## Literature search strategy

A systematic and transparent literature search was conducted following the guidelines of Levac et al. (2010)<sup>32</sup> to ensure rigour, feasibility, and reproducibility. The search was performed across multiple electronic databases to capture relevant studies, including PubMed, Scopus, Web of Science, ScienceDirect, Google Scholar, CINAHL, EBSCOHost, MEDLINE, ProQuest, and African Journals Online (AJOL). Institutional repositories and grey literature from the World Health Organization (WHO), International Labour Organization (ILO), African Union (AU), and the South African Mine Health and Safety Council (MHSC) were also searched. Searches of the World Health Organization (WHO), International Labour Organization (ILO), and African Union (AU) did not yield additional studies that met the inclusion criteria. However, these sources informed contextual understanding and reinforced the rationale for focusing on technology integration in occupational hearing conservation.

The search strategy incorporated medical subject headings (MeSH) and free-text terms, with Boolean operators, to maximise the identification of relevant literature. Key search terms were:

- 'occupational noise-induced hearing loss' OR 'ONIHL'
- 'hearing conservation programmes' AND 'occupational health'
- 'artificial intelligence in audiology' OR 'AI' AND 'occupational hearing loss'
- 'tele-audiology' AND 'occupational noise exposure'
- 'Internet of Things (IoT)' AND 'hearing protection'
- 'mHealth' AND 'hearing conservation programmes'
- 'big data analytics in occupational health' AND 'hearing loss prevention'
- 'noise exposure monitoring technology' AND 'hearing protection devices'

Supplementary search methods were adopted to source additional literature. This ensured a comprehensive review of the available literature, while maintaining transparency and reproducibility in the search strategy. To ensure relevance and methodological rigour, studies were selected based on predefined inclusion and exclusion criteria.

## Inclusion criteria

- Studies published from 2000 to 2024 (to capture recent advancements in 4IR technologies) in English
- Empirical studies, systematic reviews, meta-analyses, and policy reports focusing on:
  - o occupational noise-induced hearing loss
  - o hearing conservation programmes

- o technology-driven interventions in occupational audiology
- o regulatory frameworks for hearing conservation
- Studies from LMICs, particularly in Africa, but also including comparative global insights

## Exclusion criteria

- Studies not addressing occupational hearing loss or workplace noise exposure
- Research outside the African context (unless it provided comparative perspectives on technology adoption in LMICs)
- Studies focusing exclusively on non-occupational hearing loss or paediatric hearing impairment

Study selection and data extraction were conducted by two independent reviewers. Each reviewer screened the titles and abstracts of the identified records, assessed full texts for eligibility, and categorised the studies as highly relevant, moderately relevant, or not relevant. Discrepancies were resolved through discussion and consensus. Where disagreements could not be resolved, a third reviewer was consulted to reach a final decision.

## Data extraction and analysis

A narrative synthesis approach, consistent with established guidance for narrative reviews, such as those by Ferrari (2015),<sup>33</sup> was used to extract and analyse findings thematically across included studies. From an initial 1 147 records identified, 55 studies were assessed for relevance. Of these, 22 were selected for in-depth review (Table 1). Relevance was assessed independently by two reviewers, based on the extent to which each study addressed the objectives, technological interventions, and African or LMIC contexts.

Tables were designed to capture:

1. Study characteristics (author, year, country, study design)
2. Industry sector and worker population studied (e.g. mining, construction, manufacturing, agriculture)
3. Prevalence and impact of ONIHL and effectiveness of HCPs
4. Technological interventions explored (e.g. AI, tele-audiology, IoT-based hearing protection, big data applications)
5. Identified gaps in HCPs and technology adoption barriers
6. Policy and regulatory frameworks discussed
7. Recommendations for integrating 4IR technologies into occupational hearing conservation strategies

**Table 1. Summary of process used to select articles for final review**

Step	Description	n
Identified through database searching	Peer-reviewed journal databases and indexed searches (PubMed, Scopus, Web of Science, etc.)	1 147
Screened for relevance	Based on title and abstract review	1 147
Full-text assessed for eligibility	Comprehensive reading	55
Excluded after full-text review	Deemed not relevant	33
Identified via supplementary searches (e.g. citation tracking)*	Added to ensure completeness	11
Included in final synthesis	Highly or moderately relevant	22
Highly relevant	Directly addressed study aim and African context	10
Moderately relevant	Provided contextual or comparative insights	12

Note: supplementary searches contributed to the 55 full-text articles assessed, but did not yield articles additional to the final 22

\* included in the 55 full-text articles assessed for eligibility

A thematic analysis approach<sup>34</sup> was used to synthesise findings, categorise emerging themes, and identify patterns, challenges, and policy gaps related to ONIHL and technological interventions in African occupational health settings. Thematic saturation was reached when additional studies no longer introduced novel insights,<sup>35</sup> ensuring a comprehensive and balanced synthesis of the literature.

**Quality assurance and interpretation**

While narrative reviews offer flexibility, rigorous methodological safeguards were implemented to ensure reliability, transparency, and credibility.<sup>36</sup> These included 1) systematic documentation of the search strategy and study selection process; 2) continuous refinement of the research focus as new insights emerged; 3) critical evaluation of selected studies for methodological soundness, relevance, and applicability; and 4) reflexivity to account for potential researcher biases and contextual influences on interpretation. These measures strengthened the validity and reproducibility of the review’s findings, while ensuring a balanced synthesis of perspectives on technology-driven ONIHL management and hearing conservation in Africa.

Although formal ethical approval was not required, ethical integrity was maintained through comprehensive citation of all sources to uphold academic integrity and avoid plagiarism; use of publicly available, peer-reviewed research to ensure credibility; objective

selection and analysis of studies to minimise bias; and recognition of potential conflicts of interest and limitations in available data. Additionally, efforts were made to incorporate diverse perspectives, recognise gaps in existing research, and ensure transparency in reporting and interpretation of findings.<sup>37,38</sup>

**RESULTS AND DISCUSSION**

The results of this analysis are presented thematically to illustrate both the scope of technological innovation and the contextual challenges unique to the African occupational health environment.

The 22 studies analysed varied in study design, geographic focus, and industry sector. Ten were considered to be highly relevant (Table 2) and 12 to be moderately relevant (Table 3). The majority were literature reviews, observational studies, policy analyses, and experimental research, exploring ONIHL and HCPs within African and LMIC contexts. Most were conducted in Africa – primarily South Africa<sup>2,17,17</sup> and Nigeria;<sup>13</sup> several were from outside Africa, including western India<sup>15</sup> and Malaysia<sup>14</sup> (for comparative insights), while others did not specify a geographic focus but offered insights applicable to LMIC settings. For clarity, the tables indicate the country or region (where known). Most were qualitative reviews,<sup>2,7</sup> cross-sectional analyses of HCPs,<sup>11,12</sup> and technology-focused experimental studies on AI and IoT applications.<sup>17,39</sup>

**Table 2. Comprehensive evidence synthesis of technology-driven approaches to ONIHL and HCPs in the African context (highly relevant sources)**

Author (year), country	Industry sector, worker population	Prevalence/impact of ONIHL and effectiveness of HCPs	Technological interventions explored	Gaps in HCPs and technology adoption barriers	Recommendations for integrating 4IR technologies
Moroe and Khoza-Shangase (2022), <sup>30</sup> not specified – LMIC insights	Not specified, focus on general principles	Discusses HCPs and the industrial revolutions	Not specified	Not specified	Integrating 4IR technologies into HCPs
Madahana et al. (2022), <sup>19</sup> South Africa	Mining	Effects of changes in mining practices on ONIHL	Impact of AI and fully-automated systems	Manual vs automated systems	Implementing AI in ONIHL management
Sandström et al. (2016), <sup>21</sup> South Africa	Underserved primary healthcare contexts	Not specified	Smartphone threshold audiometry	Not specified	Using smartphone audiometry in hearing care
Khoza-Shangase and Moroe (2020), <sup>29</sup> South Africa	Not specified, focus on general principles	South African HCPs	Tele-audiology	Tele-audiology in hearing conservation	Using tele-audiology in HCPs
Danielson (2007), <sup>40</sup> not specified – comparative perspective	Not specified, focus on general principles	Not specified	Contemporary technology for hearing conservation audiometric monitoring	Not specified	Using contemporary technology in audiometric monitoring
Mahomed-Asmail and Swanepoel (2022), <sup>20</sup> sub-Saharan Africa	Not specified, focus on general principles	Not specified	mHealth solutions in hearing care	Not specified	Using mHealth solutions in hearing care
Tank et al. (2024), <sup>15</sup> Western India	Mining	Prevalence and predictors of high-frequency hearing loss	Not specified	Need for comprehensive HCP	Implementing comprehensive HCPs
AlSamhori et al. (2024), <sup>18</sup> not specified – LMIC insights	Not specified, focus on general principles	Not specified	AI for hearing loss prevention, diagnosis, and management	Not specified	Using AI for hearing loss management
Mahomed-Asmail et al. (2024), <sup>39</sup> South Africa	Not specified, focus on general principles	Not specified	Trends in digital hearing health and computational audiology	Not specified	Using digital hearing health and computational audiology
Madahana et al. (2024), <sup>17</sup> South Africa	Mining	Not specified	Development of an AI-based ONIHL early warning system	Not specified	Developing AI-based early warning systems

4IR: fourth industrial revolution, AI: artificial intelligence, HCP: hearing conservation programme, LMIC: low- and middle-income country, ONIHL: occupational noise-induced hearing loss  
 Note: policy and regulatory frameworks not consistently specified across included studies; column removed for clarity

Mining was the most studied industry,<sup>7,12,17,19</sup> reflecting the high risk of ONIHL due to chronic noise exposure. Other high-risk industries included iron and steel production,<sup>11</sup> and wood sawmills,<sup>13</sup> where workers are exposed to prolonged high-decibel noise. Several studies<sup>4,20,29</sup> examined general occupational hearing conservation strategies, applicable across multiple industries.

In the studies, a range of 4IR technologies aimed at improving ONIHL prevention were analysed, including: 1) AI for predictive audiology and threshold shift detection,<sup>17,18</sup> 2) tele-audiology for remote hearing screenings and monitoring,<sup>21,29</sup> 3) mHealth solutions for mobile HCPs,<sup>20</sup> and 4) IoT-based hearing protection and noise exposure monitoring.<sup>23,40</sup> Despite these advancements, many studies also identified key barriers to adoption, particularly in African contexts, where digital health infrastructure and policy enforcement remain underdeveloped.

Thematic analysis of the data highlighted advancements in technology-driven approaches to ONIHL prevention and HCPs, particularly through the integration of AI, tele-audiology, mHealth, IoT, and digital audiology solutions, as shown in Tables 2 and 3. While these technologies present

a paradigm shift in occupational hearing healthcare, their adoption in Africa remains limited by structural, funding, and policy-related challenges. The highly relevant studies provided direct insights into technology use in African occupational hearing conservation, while the moderately relevant studies offered critical context – particularly around implementation barriers such as cost, infrastructure limitations, and regulatory delays. Findings from both groups were integrated thematically to provide a comprehensive synthesis.

Table 2 shows the synthesis of evidence from highly relevant sources, focusing on technology-driven approaches to ONIHL management and HCPs. The themes that emerged highlight the increasing recognition of AI, tele-audiology, digital health solutions, and contemporary technology in addressing ONIHL in Africa.

### Theme 1: Increasing recognition of AI in ONIHL management

Several studies have emphasised the transformative role of AI in ONIHL prevention, particularly through early warning systems and predictive analytics in improving ONIHL detection and management.<sup>17-19</sup> Artificial intelligence has been shown to enhance audiometric surveillance in

**Table 3. Comprehensive evidence synthesis of technology-driven approaches to ONIHL and HCPs in the African context (moderately relevant sources)**

Author (year), country	Industry sector, worker population	Prevalence/impact of ONIHL and effectiveness of HCPs	Technological interventions explored	Gaps in HCPs and technology adoption barriers	Recommendations for integrating 4IR technologies
Ebekozien et al. (2023), <sup>13</sup> Nigeria	Wood sawmills	Hazards in wood sawmills	4IR technologies	Not specified	Role of 4IR technologies
Maswanganyi (2021), <sup>16</sup> South Africa	Mining (underground gold mine)	Not specified	4IR and industry 4.0 considerations	Not specified	Consider Industry 4.0
McBride (2004), <sup>12</sup> not specified – comparative perspective	Mining	Noise-induced hearing loss and hearing conservation	Not specified	Not specified	Effective implementation of hearing conservation
Mizan et al. (2014), <sup>11</sup> South Africa	Iron and steel industry	Noise-induced hearing loss and hearing conservation	Not specified	Not specified	Effective implementation of hearing conservation
Moroe and Khoza-Shangase (2020), <sup>2</sup> South Africa	Not specified, focus on general principles	Recent advances in HCPs	Not specified	Not specified	Advances in HCPs
Rogers et al. (2009), <sup>44</sup> not specified – comparative perspective	Not specified, focus on general principles	What makes a successful HCP?	Not specified	Not specified	Elements of successful HCPs
Moroe et al. (2018), <sup>7</sup> Africa	Mining	Management of ONIHL	Not specified	Not specified	Managing ONIHL in mining
Yuen (2014), <sup>14</sup> Malaysia	Not specified, focus on general principles	Environmental and occupational noise pollution	Not specified	Not specified	Addressing noise pollution
Patel et al. (2001), <sup>10</sup> not specified – comparative perspective	Not specified, focus on general principles	Barriers to preventive health actions for ONIHL	Not specified	Barriers to preventive actions	Overcoming barriers to prevention
Chis et al. (2025), <sup>26</sup> not specified – comparative perspective	Industrial environments	Integrated noise management strategies	Not specified	Not specified	Integrated noise management strategies
Waterworth et al. (2022), <sup>27</sup> not specified – focus on LMICs	Not specified, focus on general principles	Barriers to access to ear and hearing care services in LMICs	Not specified	Barriers to access	Improving access to ear and hearing care
Madahana et al. (2019), <sup>41</sup> not specified – LMIC insights	Mining	Mineworkers threshold shift estimation	Optimisation algorithms for deep recurrent neural networks	Not specified	Using optimisation algorithms for threshold shift estimation

4IR: fourth industrial revolution, HCP: hearing conservation programme, LMIC: low- and middle-income country, ONIHL: occupational noise-induced hearing loss  
Note: policy and regulatory frameworks not consistently specified across included studies; column removed for clarity

threshold shift detection, automate audiometric screenings, and facilitate occupational risk assessment in South African mining industries, where manual hearing monitoring remains a challenge. Mahomed-Asmail et al. (2024) identified AI-driven computational audiology as a promising tool for personalised hearing healthcare.<sup>39</sup> Similar applications have been reported in Europe, where AI models improved occupational hearing screening efficiency.<sup>22</sup>

These findings, suggesting a growing acknowledgment of AI's role in addressing ONIHL proactively, align with global literature,<sup>22</sup> which supports AI's potential in occupational health monitoring, early detection of hearing loss, and data-driven decision-making. However, Africa lags in AI implementation, largely due to 1) lack of digitised patient data, limiting AI training models, 2) high costs of AI-based audiometry solutions, making them inaccessible in resource-limited settings, and 3) absence of policy frameworks to support AI integration in occupational health. While countries such as South Africa have begun to explore AI for ONIHL prevention in the mining industry, its full implementation remains fragmented and largely research-driven rather than practice-driven.<sup>29</sup> Without infrastructure investment and regulatory oversight, AI in ONIHL management will remain an underutilised potential in Africa.

### Theme 2: Tele-audiology and digital health solutions in HCPs

Researchers<sup>20,21,29</sup> have highlighted the viability of tele-audiology and mHealth solutions in improving access to hearing conservation services. Khoza-Shangase and Moroe (2020)<sup>29</sup> highlighted tele-audiology as a viable approach to improving hearing conservation efforts, particularly in remote and underserved regions. Sandström et al. (2016) explored smartphone-based audiometry, emphasising its cost-effectiveness and feasibility in low-resource settings.<sup>21</sup> Mahomed-Asmail and Swanepoel (2022) demonstrated the potential of mHealth applications to enhance patient engagement in hearing conservation efforts.<sup>20</sup> The benefits of these digital solutions include:

- Remote audiometric screening and monitoring
- Cost-effective hearing conservation interventions
- Better patient engagement through mobile applications

These approaches that aim to improve accessibility and efficiency of hearing care services, especially in resource-limited settings, are consistent with international evidence,<sup>22</sup> which highlights the role of tele-audiology in bridging service delivery gaps in occupational health. However, Africa's digital divide presents a barrier to the adoption of tele-audiology, as noted in some of the studies presented in Table 3.<sup>10,27</sup> Key challenges include limited broadband connectivity in rural areas, low digital literacy among workers in high-risk industries, and concerns about data security and patient confidentiality in tele-audiology platforms. These barriers mirror broader healthcare system challenges in LMICs, where digital health strategies remain underdeveloped due to financial constraints and policy misalignment. Moving forward, multi-stakeholder collaboration – including government, industry leaders, and technology developers – is essential to scale up the adoption of tele-audiology in African occupational settings. In addition, studies such as those published by Waterworth et al. (2022)<sup>27</sup> and Patel et al. (2001)<sup>10</sup> emphasise that, while tele-audiology offers improved access to care, implementation is constrained by low digital literacy among workers, limited institutional readiness, and a lack of sustained funding for scaling digital platforms in occupational health.

### Theme 3: The internet of things and contemporary technology for hearing protection

The integration of contemporary technology into audiometric monitoring is noted. IoT-enabled hearing conservation has been explored in some studies,<sup>23,40</sup> emphasising the need for real-time noise exposure and audiometric monitoring and automated compliance tracking. Canetto and Voix (2008) explored wearable hearing protection devices with IoT capabilities, which allow for automated noise exposure tracking and user compliance monitoring.<sup>23</sup> In high-risk industries such as mining, construction, and manufacturing, these smart HPDs could revolutionise worker safety by providing continuous noise exposure data, sending real-time alerts when noise thresholds are exceeded, and tracking worker compliance with HPD usage. Despite these advantages, Africa has not yet adopted IoT-integrated HPDs at scale, as evidenced in some findings presented in Table 2.<sup>12,16</sup> A moderately relevant study (Maswanganyi, 2021)<sup>16</sup> showed that, despite growing discourse on Industry 4.0 (the next stage in the digital transformation of the manufacturing sector, propelled by disruptive developments such as increased data connectivity, advanced analytics, human-machine collaboration, and advancements in robotics), integration of IoT-enabled safety technologies in South African industrial settings remains rare due to prohibitive costs, low employer investment in advanced safety technologies, insufficient workforce preparedness, and lack of enforcement of workplace noise monitoring policies.<sup>16</sup> Moderately relevant studies, such as by Maswanganyi (2021)<sup>16</sup> and McBride (2004),<sup>12</sup> point to an overreliance on outdated, paper-based surveillance systems in industries like mining and steel manufacturing. These systems hinder real-time monitoring and slow the responsiveness of HCPs, reinforcing the need for digitisation.

These findings align with global reports,<sup>13,26</sup> which indicate that, while Industry 4.0 has the potential to improve OHS, adoption remains slow in developing economies. Without targeted policy incentives and employer engagement, IoT solutions for hearing conservation will remain a technological luxury rather than a standard workplace requirement in Africa.<sup>41</sup>

### Theme 4: Regulatory and implementation gaps in African HCPs

Across studies summarised in Tables 2 and 3, a recurring theme was the absence of strong policy frameworks to drive technology adoption in ONIHL prevention. Studies by Moroe and Khoza-Shangase (2020),<sup>2</sup> Madahana et al. (2022),<sup>19</sup> and Tank et al. (2024)<sup>15</sup> highlight the lack of regulatory enforcement in ONIHL prevention as a major challenge to hearing conservation efforts. Moroe and Khoza-Shangase (2020)<sup>2</sup> argue for policy updates to integrate 4IR technologies into hearing conservation strategies, particularly in industries with high noise exposure.

Study findings suggest that, while Africa has occupational health regulations, these often lack technological integration mandates for ONIHL prevention; are poorly enforced, especially in informal and small-scale industries; and do not incentivise industries to invest in hearing conservation technologies – pointing to potential implementation gaps. These results are consistent with international evidence, which suggests that policy gaps in LMICs slow down occupational health technology implementation.<sup>31,42,43</sup> Without updated and enforceable regulations, technology-driven hearing conservation solutions will remain underutilised in African workplaces.

Overall, key findings from studies in Table 2 indicate that 1) AI-based ONIHL management tools are gaining traction but remain underutilised due to cost and infrastructure challenges, 2) tele-audiology and mHealth show promise for scalable hearing HCPs in Africa, 3) the lack of integration of IoT into hearing protection devices limits real-time noise exposure tracking, and 4) policies must evolve to accommodate technological advancements, ensuring compliance with HCPs.

Studies in Table 3 highlight industrial applications of 4IR, barriers to effective hearing conservation, integration of AI and data analytics into ONIHL management, and occupational health risks in various sectors in Africa. Several moderately relevant studies, including Chis et al. (2025)<sup>26</sup> and Yuen (2014),<sup>14</sup> highlight how fragmented occupational health regulations, limited cross-sector collaboration, and a general lack of policy enforcement contribute to technology underutilisation in hearing conservation. Outdated occupational safety policies in LMICs often lack the provisions necessary to support the adoption of innovative technologies, even when such technologies are available. This reinforces the need for stronger regulatory frameworks that are responsive to digital innovation and context-specific occupational health realities. Such findings underscore that regulatory alignment is as critical to progress as technological advancement itself. The studies reviewed highlight practical challenges and broader systemic issues related to ONIHL management, offering valuable perspectives that support the conclusions of this review.

First, with regard to industrial applications of 4IR in noise management, Ebekozen et al. (2023)<sup>13</sup> and Maswanganyi (2021)<sup>16</sup> explored the role of Industry 4.0 in occupational noise management, particularly in mining and wood sawmills. Findings suggested that, while digital transformation is occurring, the adoption of noise monitoring technology remains fragmented across industries. Second, concerning barriers to effective hearing conservation in Africa, Patel et al. (2001)<sup>10</sup> and Waterworth et al. (2022)<sup>27</sup> identified accessibility, awareness, and regulatory gaps as major barriers to effective ONIHL prevention in LMICs. Yuen (2014)<sup>14</sup> and Chis et al. (2025)<sup>26</sup> examined noise pollution mitigation efforts, emphasising the need for stricter enforcement of hearing conservation policies. Third, with regard to AI and data analytics in ONIHL management, Madahana et al. (2019)<sup>41</sup> explored deep learning algorithms for ONIHL detection, advocating for AI-powered threshold shift estimation models. Rogers et al. (2009)<sup>44</sup> and Moroe et al. (2018)<sup>7</sup> highlighted the importance of predictive analytics in hearing conservation, although practical implementation in Africa remains limited by cost and digital infrastructure. Last, regarding occupational health risks and gaps in hearing protection, McBride (2004)<sup>12</sup> and Mizan et al. (2014)<sup>11</sup> focused on hearing conservation efforts in high-risk industries, particularly mining and manufacturing. They reported that many HCPs in Africa remain paper-based, with minimal adoption of digital solutions for noise exposure monitoring.

Overall, key findings from studies summarised in Table 3 were that 1) industrial adoption of 4IR technologies remains slow, particularly in hearing conservation, 2) barriers to ONIHL prevention include lack of funding, awareness, and regulatory enforcement, 3) AI-driven threshold shift estimation and predictive analytics have potential for early detection of ONIHL, targeted intervention planning, and improving the efficiency of occupational HCPs, but are underutilised, and 4) current HCPs rely on outdated, paper-based

systems, limiting real-time monitoring of worker noise exposure. Artificial intelligence-driven threshold shift estimation and predictive analytics hold significant potential for early detection of ONIHL, targeted intervention planning, and improving the efficiency of occupational HCPs.

Although African studies clearly highlight the promise and constraints of adopting 4IR technologies in occupational hearing conservation, comparisons with global literature reveal both shared and divergent challenges. For example, in high-income countries such as the United States of America and the United Kingdom, AI-driven audiometric tools and IoT-enabled noise surveillance systems are being integrated into workplace hearing conservation efforts with increasing institutional and regulatory support. However, even in these contexts, data privacy concerns, workforce resistance, and uneven implementation persist – albeit mitigated by better funding and infrastructure. In contrast, African workplaces face steeper obstacles due to systemic underinvestment in digital health infrastructure, fragmented occupational health systems, and a lack of political prioritisation for hearing loss. This global comparison highlights that, while technological solutions are not context-exclusive, the enablers for success, such as policy enforcement, digital literacy, and investment, are disproportionately lacking in LMICs, particularly in Africa. Therefore, any efforts to replicate global best practices in the African context must be adapted to local socio-economic and infrastructural realities.

### Limitations

While this review provides a comprehensive synthesis of technology-driven approaches to ONIHL prevention in Africa, several limitations must be acknowledged. The first is the heterogeneity of the included studies, which varied in methodological quality, scope, and industry focus. While efforts were made to synthesise findings systematically, the lack of uniform study designs presents comparability challenges. Second, there is limited empirical data on AI and IoT applications in Africa. While AI and IoT are widely discussed in the hearing conservation literature, empirical studies on their implementation in Africa are scarce; most focus on theoretical potential rather than real-world applications. Third, articles published in languages other than English, particularly French-, Portuguese-, and Arabic-language studies from Africa, were excluded. These articles may have described relevant research. Fourth, while efforts were made to include policy reports and grey literature, many African occupational health reports are unpublished or inaccessible, limiting insights into regulatory frameworks and real-world industry practices. Last, this review relied exclusively on published articles and grey literature, and did not include data from companies or occupational health providers. It is acknowledged that some companies in South Africa and other African countries may already be adopting elements of AI, IoT, or digital hearing conservation solutions in line with available technologies, regulatory compliance needs, and digital record-keeping requirements. However, the investigation of industry-level implementation or adoption of these technologies was outside the scope of the present review.

Despite these limitations, this review provides critical insights into the current state of, challenges to, and opportunities for technology-driven ONIHL prevention in Africa. Research into technology-based ONIHL prevention strategies in Africa must expand beyond theoretical explorations. Future investigations, comprising both global and regional collaborations, should prioritise empirical studies that evaluate the real-world implementation, feasibility,

cost-effectiveness, and scalability of AI and IoT solutions across occupational settings – enabling the co-development of scalable and context-sensitive hearing conservation strategies that respond not only to technological opportunity, but also to systemic occupational health disparities. Comparative studies across LMICs could provide insight into regional variations and transferable practices. Future research should 1) prioritise empirical evaluations of AI, IoT, and digital audiology solutions in real-world occupational settings to drive evidence-based policy changes, and 2) include industry-specific investigations to map the use, outcomes, and challenges of integrating 4IR technologies into HCPs, particularly in sectors with high ONIHL burdens such as mining, manufacturing, and construction.

Recommendations include enhanced investment in AI and IoT for ONIHL management that could lead to automated, real-time hearing conservation solutions; capacity-building initiatives to train professionals on digital hearing conservation tools; and prioritisation of Africa-specific policy reforms to ensure contextually relevant integration of 4IR technologies in occupational health. Ethical considerations – including data privacy, informed consent, and potential biases in AI-driven tools – must be addressed systematically to avoid reinforcing inequities within occupational health systems.

## CONCLUSION

This review provides a comprehensive synthesis of the role of emerging technologies in ONIHL prevention and HCPs within the African context. While advancements in AI, tele-audiology, mHealth, IoT, and digital audiology hold immense potential for revolutionising ONIHL management, their adoption remains limited due to persistent infrastructural gaps, limited funding, and outdated regulatory systems. In an era where digital transformation is shaping global healthcare systems, Africa finds itself at a crossroads – poised to integrate these technologies into occupational health frameworks, but hindered by barriers to implementation.

Rather than examining each technology in isolation, this review highlights a cross-cutting pattern of challenges that include the lack of digitised systems, limited workforce capacity, prohibitive costs, and regulatory inertia. These systemic issues continue to restrict the widespread implementation of even well-established innovations. While AI offers predictive capabilities and automated hearing assessments, and tele-audiology and mHealth can expand access to underserved regions, their effectiveness is constrained by inadequate infrastructure and limited interoperability between systems. Likewise, the integration of IoT into hearing protection offers promise for real-time noise monitoring, yet uptake remains slow due to cost constraints and the absence of incentives for industrial adoption.

Africa's regulatory frameworks for OHS are not keeping pace with technological advancements. Many policies governing hearing conservation remain outdated, lacking explicit mandates for integrating digital health solutions or supporting data-driven monitoring systems. Without strong regulatory enforcement, industry-driven HCPs remain fragmented and, in some cases, ineffective in addressing the long-term risks of ONIHL. Given the disproportionate burden of noise-induced hearing loss in high-risk sectors such as mining, manufacturing, and construction, urgent policy reform is required to align occupational health governance with the realities and demands of the 4IR.

To advance the integration of emerging technologies into ONIHL prevention, a coordinated, multi-sectoral approach is essential. Governments, industries, and healthcare professionals must

co-develop standardised protocols that promote the responsible and sustainable use of AI, tele-audiology, and IoT in occupational health. Investment in digital infrastructure – particularly in rural and industrial regions – must be paired with targeted capacity-building initiatives to equip occupational health professionals with the digital competencies needed to deploy and manage these tools. Public-private partnerships and government-backed incentives can play a vital role in encouraging industries to adopt technology-driven hearing conservation strategies.

Ultimately, this review underscores the fact that, while Africa is well-positioned to benefit from 4IR technologies, the path to meaningful implementation will require sustained effort, strategic investment, agile policymaking, and evidence-based collaboration. By aligning occupational health priorities with global digital innovation trends, Africa can significantly reduce the burden of work-related hearing loss and secure the long-term auditory health of its workforce. The convergence of technology and occupational audiology presents an unprecedented opportunity to modernise HCPs, and this must be embraced with urgency and strategic foresight. Looking ahead, the African experience regarding ONIHL prevention offers valuable lessons for other LMICs grappling with similar resource and policy constraints.

## DECLARATION

The author declares that this is her own work; all the sources used in this paper have been duly acknowledged and there are no conflicts of interest.

## Author's contributions

This is a sole-authored review, where the author conceptualised the study and conducted the research, analysed the data, and wrote the manuscript.

## KEY MESSAGES

1. Emerging technologies – such as AI, tele-audiology, mHealth, and IoT – can transform the prevention and management of ONIHL in Africa.
2. Fourth industrial revolution technologies have the potential to support early detection, real-time noise exposure monitoring, and personalised hearing protection, particularly in high-risk industries.
3. Implementation barriers in LMICs include inadequate digital infrastructures, regulatory shortcomings, and limited industry incentives.
4. The findings provide practical guidance for policymakers, occupational health professionals, and industry leaders aiming to modernise HCPs.

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