

Proposed Design Improvements for Earplugs Considering the Factors Affecting Their Comfort

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ABSTRACT

The low compliance with earplug uses in Indonesian workplaces reflects suboptimal occupational safety and health (K3) implementation, particularly in protecting workers from noise exposure, with discomfort cited as a primary cause. This study investigates factors influencing earplug comfort and proposes user-oriented design improvements. Comfort was measured using the comfort of hearing protection device (COPROD) questionnaire which has been applied in many countries and areas across four dimensions that include physical, functional, acoustic, and psychological, based on responses from 458 users. Data were analyzed using partial least squares structural equation modeling (PLS-SEM) and importance-performance map analysis (IPMA). Results show all four dimensions significantly affect overall comfort, with physical comfort emerging as the most critical yet underperforming factor, making it the primary target for enhancement. Functional comfort also demonstrated below-average performance but with lower relative importance, positioning it as a secondary priority. Key comfort attributes were then converted into functional and technical requirements, informing targeted design interventions to improve earplug performance and user acceptance.

Keywords: earplug, physical comfort, functional comfort, acoustical comfort, psychological comfort

1. Introduction

The implementation of occupational safety and health (OSH) programs yields significant benefits for both employees and companies, whereas neglecting OSH can cause severe losses, including physical injury, psychological disorders, increased compensation costs, production disruptions, and reputational decline (Kim & Park, 2021). OSH contributes substantially to employee productivity, with an influence of 72.8% reported by Firman (2022). One critical OSH aspect is workplace noise, defined as unwanted sound that interferes with normal activities (Liu et al., 2022). High noise exposure impairs attention, working memory, and productivity (Dean, 2024) and, at ≥ 6000 Hz, leads to significantly lower performance levels (Toker et al., 2025). Physiologically, optimal conditions occur at ~ 50 dBA, with deviations affecting heart rate variability indicators such as SDNN and normalized-HF; a 10 dBA increase below 50 dBA improves physiological condition by 5.4%, whereas above 50 dBA it decreases by 1.9% (Srinivasan et al., 2023). Prolonged exposure can cause noise-induced hearing loss (NIHL), which is linked to reduced speech comprehension, depressive symptoms, social isolation, and decreased work performance (Abbasi et al., 2024).

In Indonesia, around 74.5% of construction workers are exposed to occupational noise, with 51% reporting hearing-related complaints (Ambar & Suraya, 2022). Noise from heavy machinery ranges between 80–120 dB, exceeding OSHA's permissible exposure limit of 90 dBA (Aiyer, 2021). Hearing protection devices (HPDs), such as earplugs, effectively reduce NIHL risk (Kwak & Han, 2021), yet compliance remains low. For example, in ground handling workers at Kualanamu International Airport, 85.3% of those not using earplugs experienced hearing loss compared to only 33.3% among users (Ramadhani, Silaban, & Hasan, 2017). Discomfort is a primary barrier to consistent HPD use (Doutres et al., 2022), with factors such as poor fit, excessive pressure inside the ear canal, and reduced concentration cited in preliminary studies, where 85% of surveyed workers admitted not fully utilizing earplugs in noisy areas.

Earplugs are favored over earmuffs due to their smaller size, portability, and compatibility with other personal protective equipment, and are perceived as more comfortable in humid environments (MEL Safety Institute, 2023; NIH, 2025). However, their protective effectiveness depends heavily on proper insertion, making comfort a critical determinant of sustained use (Guo et al., 2024). Terroir et al. (2022) state that perceived comfort depend on

physical and psychosocial characteristics of the environment, person, and the earplug; which differ from one country to another.

To address the issue, the Comfort of Hearing Protection Device (COPROD) questionnaire is recommended for assessing four key comfort dimensions: physical, functional, acoustic, and psychological (Negrini et al., 2024). COPROD has been applied in designing ear plug in several countries and has been proved to be an effective tool (e.g., Terroir et al., 2022; Wang et al., 2024). Evidence shows these dimensions significantly influence overall comfort, and prioritizing the most impactful yet underperforming factors can inform user-centered design improvements. This study applies COPROD to Indonesian workers to identify such factors and develop earplug designs that enhance comfort, promote consistent use, and ultimately reduce NIHL prevalence in noisy occupational environments.

1.1 Objectives

This research holds significance in advancing occupational safety practices by addressing comfort-related barriers to earplug use, a critical factor influencing compliance in noisy work environments. By applying the COPROD framework to identify and prioritize physical, functional, acoustic, and psychological comfort dimensions among Indonesian workers, the study provides evidence-based insights for user-centered earplug design. The objectives of this study, derived from the background analysis and problem formulation, are as follows:

1. To identify the factors contributing to the overall comfort of earplugs.
2. To propose improvements to specific attributes to enhance earplug comfort for users in Indonesia.

2. Literature Review

Previous studies on hearing protection devices (HPDs), particularly earplugs, have established that user comfort significantly influences consistent and correct usage in occupational settings. Comfort in HPDs is a multidimensional construct encompassing physical, functional, acoustical, and psychological aspects, as defined in the COPROD framework. Negrini et al. (2024) developed and validated a structural model using Partial Least Squares Structural Equation Modeling (PLS-SEM) to quantify the contribution of these dimensions to overall comfort. This approach enables robust analysis of latent variables and complex interrelationships, making it particularly relevant for ergonomics-related product evaluation. In this research, the COPROD-based comfort dimensions serve as the theoretical model, and PLS-SEM is applied to assess measurement validity, reliability, and the significance of hypothesized relationships.

Following the PLS-SEM analysis, Importance–Performance Map Analysis (IPMA) is employed to identify key comfort attributes that are both highly influential and underperforming. IPMA extends traditional PLS-SEM results by mapping each construct's importance (total effects on the target construct) against its performance (average latent variable scores), providing actionable insights for prioritizing design improvements. Within the context of earplug development, this dual-criteria evaluation helps target interventions toward attributes with the highest potential impact on user satisfaction and compliance. The integration of PLS-SEM and IPMA thus provides a comprehensive analytical framework for understanding comfort determinants and informing ergonomic design enhancements tailored to the needs of Indonesian workers.

3. Conceptual Model

This study employs a higher-order reflective model of overall comfort (OC) in earplug use, grounded in the multidimensional comfort framework of Doutres et al. (2020), Negrini et al. (2024), and Terroir et al. (2021). OC is represented by four lower-order constructs that include physical comfort (PHC), functional comfort (FUC), acoustical comfort (ACC), and psychological comfort (PSC) that are measured through indicators adapted from the COPROD instrument and contextualized for Indonesian occupational environments. PHC concerns biomechanical and thermal fit; FUC addresses usability and operational stability; ACC captures environmental sound perception and occlusion effects; and PSC reflects emotional and cognitive responses, including adaptation and satisfaction. Preliminary qualitative analysis confirmed that user-reported discomfort reasons aligned with these dimensions, supporting construct validity. Prior research indicates all four dimensions significantly predict OC, with psychological and functional comfort showing the strongest influence. Conceptual model used in this research is shown in Figure 1.

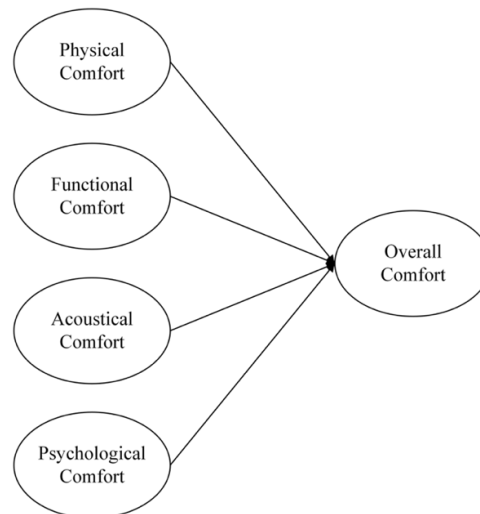


Figure 1. Conceptual model

4. Methods

The research followed a structured methodology comprising four main stages: data collection, model evaluation using Partial Least Squares Structural Equation Modeling (PLS-SEM), Importance-Performance Map Analysis (IPMA), and recommendation formulation. The process began with preliminary studies and literature review to define constructs of earplug comfort adapted from previous validated models. A questionnaire was developed and translated according to International Test Commission (2020) guidelines, followed by pilot testing and full-scale data collection from Indonesian workers aged 18–60 who use earplugs in noisy work environments, applying judgmental sampling with a minimum sample size of 385 calculated using Cochran’s method. PLS-SEM was employed to evaluate the measurement and structural models through indicator reliability, internal consistency, convergent and discriminant validity, collinearity diagnostics, and path significance testing. IPMA was then applied to map comfort dimensions based on their relative importance to overall comfort and their performance scores, identifying high-impact, low-performance attributes as design priorities. The findings informed ergonomic design recommendations for earplugs and managerial implications for product development strategies.

5. Data Collection

Data were collected using a COPROD-based questionnaire (Terroir et al., 2021) adapted for Indonesian respondents through forward-backward translation with expert review to ensure semantic equivalence. The instrument employed a five-point Likert scale for most items, with selected indicators using semantic differential scales, and was administered via non-probability judgmental sampling. The minimum sample size of 385 was calculated using Cochran’s formula (95% confidence level, 5% precision). After pilot testing with five respondents, the survey was distributed online via Google Forms, yielding 459 responses. Preprocessing included missing data analysis (none found), detection and removal of straight-line patterns ($n = 2$) using MiniTab, and identification of univariate and multivariate outliers via Grubb’s test and Mahalanobis distance in SPSS ($n = 40$, $p < 0.001$). All indicators met normality criteria (skewness -1 to $+1$, kurtosis -3 to $+3$). The final dataset comprised 417 valid responses, exceeding the required sample size for robust Partial Least Squares Structural Equation Modeling (PLS-SEM) analysis.

6. Result and Discussion

This section presents the respondent profile, followed by model evaluation using Partial Least Squares Structural Equation Modeling (PLS-SEM) and Importance-Performance Map Analysis (IPMA). PLS-SEM assesses the reliability, validity, and significance of relationships between comfort dimensions and overall comfort, while IPMA identifies high-importance, low-performance attributes to guide ergonomic earplug design improvements.

6.1 Respondent Profiles

The respondent profile shown in Table 1 indicated that the majority were aged 18–44 years (96.88%), with a nearly balanced distribution between university graduates (52.04%) and non-university education (47.96%). Over half (52.04%) had used earplugs for several years, while 32.13% had used them for several months and 15.83% for only a few days. Most respondents reported using earplugs due to company regulations (65.71%), with roll-down foam types being the most common (53.24%), followed by premolded (26.14%) and custom types (20.62%). The predominant usage duration was several hours per day (58.27%), with smaller proportions using them for a full day (25.90%) or only a few minutes (15.83%).

Table 1. Respondent profile

Variable	Categories	N	%
Age	18-44 years	404	96,88%
	>44 years	13	3,12%
Education	Non-university	200	47,96%
	University	217	52,04%
Earplug usage experience	Some days	66	15,83%
	Some months	134	32,13%
	Some years	217	52,04%
Reason for earplug use	Personal choice	143	34,29%
	Company regulations	274	65,71%
Earplug type	<i>Roll-down foam</i>	222	53,24%
	<i>Premolded</i>	109	26,14%
	<i>Custom</i>	86	20,62%
Daily duration of use	A few minutes	66	15,83%
	A few hours	243	58,27%
	All day long	108	25,90%

Independent samples *t*-tests shown in Table 2 were conducted to examine whether demographic variables significantly influenced perceived overall comfort. Variables tested included age, education, earplug use experience, reason for use, earplug type, and usage duration. At a 95% confidence level, the results showed that only earplug use experience had a statistically significant effect ($p = 0.037$), with respondents using earplugs for a few days or months reporting higher comfort compared to those with several years of use. Other demographic variables showed no significant differences ($p > 0.05$), indicating that perceived comfort was generally consistent across these groups.

Table 2. Statistical difference test of demographic variables

Variable	Category	Mean	Significance	
			<i>t-statistics</i>	<i>p-value</i>
Age	18-44	2,92	0,452	0,326
	>44	2,85		
Education	Non-university	2,93	0,391	0,348
	University	2,91		
Earplug usage experience	Some days/months	2,9	1,792	0,037
	Some years	2,91		
Reason for earplug use	Personal choice	2,92	-0,444	0,329
	Company regulations	2,89		
Jenis Earplug type	Custom	2,92	-0,478	0,316
	Others	2,910		
Daily duration of use	A few minutes/hours	2,910	-0,479	0,316
	All day long	2,934		

6.2 Model Evaluation

The results of the model evaluation confirmed that the measurement model met the required reliability and validity thresholds, while the structural model demonstrated significant and meaningful relationships between constructs. These findings validate the robustness of the proposed conceptual framework and provide a sound basis for further analysis.

6.2.1 Reliability and convergent validity

The convergent validity assessment, conducted through outer loading and Average Variance Extracted (AVE) analysis, resulted in the removal of four indicators (ACC1, ACC2, ACC3, and ACC6) that failed to meet the minimum acceptable thresholds. Following their removal, all indicators achieved outer loadings ≥ 0.700 , and all constructs, including the higher-order construct of Overall Comfort, met the AVE criterion of ≥ 0.500 , confirming convergent validity. Composite reliability values for all constructs were ≥ 0.700 , indicating strong internal consistency and demonstrating that indicators within each construct were highly correlated and effectively measured the same latent concept. The assessment is shown in Table 3.

Table 3. Convergent validity and reliability

Construct	Indicator	Convergent Validity		Reliability
		Outer Loading	AVE	Composite Reliability
<i>Physical Comfort</i>	PHC1	0,852		
	PHC2	0,842		
	PHC3	0,889		
	PHC4	0,872	0,747	0,944
	PHC5	0,857		
	PHC6	0,71		
	PHC7	0,705		
<i>Functional Comfort</i>	FUC1	0,899		
	FUC2	0,888		
	FUC3	0,897		
	FUC4	0,862		
	FUC5	0,879		
	FUC6	0,871		
	FUC7	0,873		
	FUC8	0,882		
	FUC9	0,867	0,772	0,982
	FUC10	0,906		
	FUC11	0,863		
	FUC12	0,877		
	FUC13	0,872		
	FUC14	0,865		
	FUC15	0,871		
	FUC16	0,859		
	FUC17	0,905		

Construct	Indicator	Convergent Validity		Reliability
		<i>Outer Loading</i>	AVE	<i>Composite Reliability</i>
<i>Acoustical Comfort</i>	ACC4	0,908	0,826	0,948
	ACC5	0,912		
	ACC7	0,899		
	ACC8	0,899		
	ACC9	0,888		
<i>Psychological Comfort</i>	PSC1	0,717	0,788	0,933
	PSC2	0,872		
	PSC3	0,857		
	PSC4	0,886		
	PSC5	0,9		
<i>Overall Comfort</i>	OC		0,504	0,976

6.2.2 Discriminant validity

The discriminant validity evaluation conducted using cross-loadings, Fornell-Larcker Criterion (FLC), and heterotrait-monotrait ratio (HTMT), confirmed that all constructs were empirically distinct. Cross-loading analysis showed each indicator's loading on its associated construct exceeded its loadings on other constructs. FLC results shown in Table 4 indicated that the square root of AVE for each construct was greater than its correlations with other constructs, with exceptions explained by the repeated-indicator approach for higher-order constructs.

Table 4. FLC values

	ACC	FUC	OC	PHC	PSC
ACC	0,909				
FUC	0,165	0,879			
OC	0,291	0,949	0,71		
PHC	0,275	0,586	0,786	0,864	
PSC	0,228	0,461	0,662	0,663	0,888

HTMT values shown in Table 5 were below the recommended threshold of 0.85, indicating no discriminant validity concerns. Overall, the model satisfied all discriminant validity criteria.

Table 5. HTMT values

	ACC	FUC	PHC	PSC
ACC				
FUC	0,171			
PHC	0,29	0,608		
PSC	0,242	0,482	0,706	

6.2.3 Collinearity test

The collinearity assessment using the Variance Inflation Factor (VIF) shown in Table 6 indicated no multicollinearity issues among the lower-order constructs (PHC, FUC, ACC, and PSC). All VIF values ranged from 1.086 to 2.222, well below the threshold of 5 recommended by Hair et al. (2021), confirming that the model doesn't have collinearity problems.

Table 6. VIF values

Konstruk	VIF
ACC	1,086
FUC	1,544
PHC	2,222
PSC	1,817

6.2.4 Path coefficient significance test

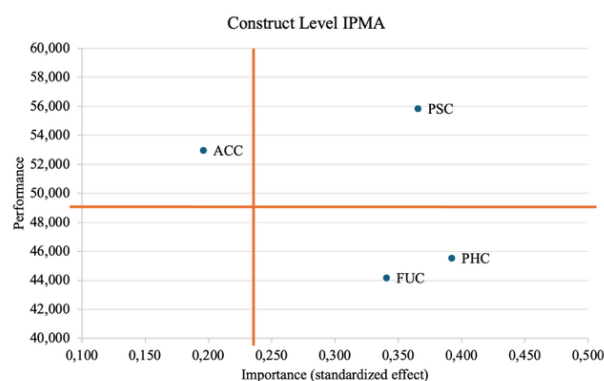
The path coefficient significance test, performed using bootstrapping that is shown in Table 7, demonstrated that all hypothesized relationships between the lower-order constructs (physical comfort, functional comfort, acoustical comfort, and psychological comfort) and the higher-order construct of overall comfort were statistically significant and positively correlated. All path coefficients ranged from 0.189 to 0.635, with positive values indicating that higher levels of each comfort dimension were associated with higher overall comfort. Furthermore, all t-statistics greatly exceeded 1.96 and p-values were <0.001, confirming that each construct made a unique and meaningful contribution to explaining overall comfort.

Table 7. Hypothesis testing

No	Hypothesis	Path Coefficient	T-statistics	P- values
H1	PHC -> OC	0,262	56,882	<0,001
H2	FUC -> OC	0,635	69,4	<0,001
H3	ACC -> OC	0,193	49,262	<0,001
H4	PSC -> OC	0,189	48,409	<0,001

6.3 IPMA

The Importance-Performance Map Analysis (IPMA) identified priority areas for improving earplug comfort by mapping each construct's standardized importance (effect) and performance scores into four quadrants. At the construct level shown in figure 2, physical comfort (importance = 0.392; performance = 45.540) and functional comfort (importance = 0.341; performance = 44.181) were categorized as "concentrate here," indicating high importance but relatively low performance, thus requiring targeted improvement. Acoustical comfort (importance = 0.196; performance = 52.952) fell into the "possible overkill" category, suggesting performance exceeded its relative importance, while psychological comfort (importance = 0.365; performance = 55.836) was placed in "maintain the good work," showing both high importance and high performance.

**Figure 2.** Costruct level IPMA

At the indicator level shown in Figure 3, most functional comfort indicators were classified as "low priority," except FUC9 ("possible overkill"), indicating that while performance was relatively high, its importance was low. Acoustical comfort indicators were spread across quadrants, with ACC5, ACC7, and ACC8 categorized as "maintain the good work," ACC4 as "possible overkill," and ACC9 as "low priority." All psychological comfort indicators aligned with their construct in "maintain the good work." Physical comfort indicators were primarily in

“concentrate here,” except PHC1 and PHC7, which were in “maintain the good work,” highlighting potential strengths to be preserved alongside areas requiring performance enhancement.

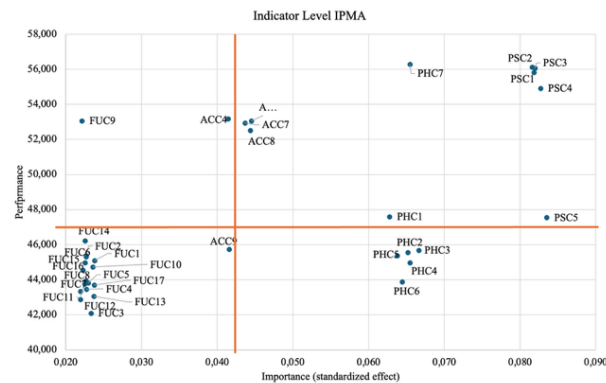


Figure 3. Indicator level IPMA

6.4 Design Solutions

Based on the Importance–Performance Map Analysis (IPMA), the primary design improvement priorities lie within the physical comfort dimension, specifically indicators PHC2, PHC3, PHC4, PHC5, and PHC6. These indicators represent core customer needs related to avoiding pain during earplug insertion, use, and removal, as well as ensuring softness and smoothness in contact with the skin. Such needs are directly tied to users’ perceptions of comfort and long-term usability, which are critical determinants of hearing protection compliance (Casali & Gerges, 2007).

The process of translating customer needs into functional requirements ensures that the design team can focus on the essential functions the product must perform (Sommerville, 2016). For PHC2–PHC4, the key functional requirement is even pressure distribution across all contact surfaces with the ear canal, preventing localized pressure points that cause discomfort. For PHC5, the functional requirement is minimal skin pressure to reduce irritation and fatigue during prolonged wear. For PHC6, the requirement is low surface roughness, which facilitates smoother insertion and removal while minimizing friction-induced irritation.

Functional requirements are then converted into engineering requirements, which are objective, measurable design parameters enabling performance verification (Franceschini, 2002). For even pressure distribution (PHC2–PHC4), the engineering requirement is the ratio of the product’s cross-sectional area to material density (EC1), ensuring adequate stiffness without excessive localized compression. For minimal skin pressure (PHC5), the engineering requirement is low-density viscoelastic material (EC2), which balances cushioning with structural stability. For low surface roughness (PHC6), the requirement is a low skin–material friction coefficient (EC3) to reduce mechanical resistance during insertion.

From these engineering requirements, targeted design improvement solutions were formulated:

1. PHC2–PHC4 (Even Pressure Distribution) – Redesign the earplug shape to eliminate protruding sections in contact with the ear canal, ensuring uniform pressure distribution. The geometry should maintain mechanical stability while avoiding excessive compression. This approach addresses both comfort and fit, and may be combined with morphology-based shaping strategies to enhance sealing efficiency (Casali & Gerges, 2007).
2. PHC5 (Minimal Skin Pressure) – Modify the base material, such as memory foam or polyurethane viscoelastic foam (PVF), to reduce density and improve viscoelasticity. Techniques include the addition of luffa seed oil (LSO), which has been shown to lower hardness in PVF (Zhang, 2022), or NaCl inclusion in silicone formulations to reduce tensile strength and density (Peng, 2021). This ensures a softer contact surface while maintaining acoustic attenuation properties.
3. PHC6 (Low Surface Roughness) – Apply a surface coating with a low skin–material friction coefficient, such as polyester mesh fabric or polyester weft-knitted fabric (Li, 2018). These materials provide a smoother tactile feel, reducing insertion resistance and minimizing the risk of skin abrasion during extended use (Podulka, 2022).

The same translation process was applied to the remaining low-priority improvements, covering functional comfort (e.g., mechanical simplicity, stable sound attenuation, ease of cleaning) and their respective engineering requirements (e.g., sound absorption coefficient, dimensional fit, water contact angle). Corresponding solutions include symmetrical earplug design to simplify handling, morphology-based shaping to improve sealing, hydrophobic surface modification to enhance cleanability, and the selection of materials with high thermal conductivity for hot environments (Gao & Zhu, 2009; Lizák & Mojumdar, 2015). Consistent result has been found in other studies using COPROD (for example studies by Terroir et al. 2022 and Wang et al. 2024). However, further studies are needed to examine the generality of the existing result. Next research considering another method will enrich the result and analysis as well.

By systematically mapping subjective customer needs into quantifiable engineering requirements and then into implementable design solutions, this approach ensures that product development decisions are both user-centered and technically verifiable, supporting comfort improvement without compromising earplug safety or compliance with EN-352 standards.

Conclusions

This study identified that all four comfort dimensions which include physical comfort, functional comfort, acoustical comfort, and psychological comfort, significantly contribute to the overall comfort of earplug use. IPMA analysis revealed that physical comfort holds the highest importance yet requires performance improvement, particularly in reducing pain during insertion, use, and removal, as well as enhancing softness and surface smoothness. Functional comfort also demonstrated suboptimal performance, albeit with lower importance.

To address these findings, user needs were systematically translated into functional requirements and subsequently into measurable engineering requirements. This process yielded eight design improvement solutions, with three high-priority recommendations: (1) designing earplugs without protrusions in contact areas to ensure uniform pressure distribution; (2) modifying materials such as memory foam or polyurethane viscoelastic foam (PVF) with additives (e.g., luffa seed oil or NaCl) to reduce density and enhance viscoelasticity; and (3) applying low-friction coatings, such as polyester mesh fabric, to improve perceived softness. Additional solutions include enhancing sound attenuation, adopting symmetrical designs for ease of use, tailoring shapes to ear canal morphology, increasing hydrophobicity, and selecting high thermal conductivity materials for tropical climates.

These findings provide a clear prioritization framework for earplug design improvements. Developers are advised to first focus on enhancing physical comfort, followed by optimizing functional comfort, while considering cost constraints, material availability, and potential design trade-offs. With adherence to international standards such as EN 352, these solutions have the potential to produce earplugs that are not only comfortable but also safe and compliant with regulatory requirements.

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