

Knowledge, Attitude, and Practice Regarding Biomedical Waste Management Among Healthcare Workers in Aden, Yemen: A Multilevel Cross-Sectional Study

Ali N.M. Gubran

a.Alyafei@aden.ust.edu

University of Science and Technology

Hanan A. A. Mohammed

University of Science and Technology

Naif Taleb Ali

University of Science and Technology

Esra Hani Abdo Qasem

University of Science and Technology

Siba Mamoon Anis Abdo Ahmed

University of Science and Technology

Abdulrahman Mohsen Mohammed Abdurabu

University of Science and Technology

Shahd Shawqi Ghazi Abdo Esmail

University of Science and Technology

Ahmed Bin Nasser

University of Science and Technology

Zayed Ali Abdullah Khalifi

University of Science and Technology

Ekhlas Abdulraheem Salem Al-Shaibah Al_Awlaqi

University of Science and Technology

Hanadi Mohammed Hamood Zain

University of Science and Technology

Bakr Faisal Said Naji

University of Science and Technology

Ahmed Shawqi Abdulwahed Ali

University of Science and Technology

Naif Mohammed Al-Haidary

Sana'a University

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Abstract

Background

Biomedical waste (BMW) management is critical for infection prevention and occupational safety in healthcare settings. In conflict-affected regions such as Yemen, healthcare infrastructure has been severely compromised, yet comprehensive data on healthcare workers' (HCWs) knowledge, attitudes, and practices (KAP) regarding BMW management remain scarce. This study aimed to assess KAP regarding BMW management among HCWs in Aden, Yemen, and identify individual- and facility-level factors associated with good practices.

Methods

A facility-based cross-sectional study was conducted from January to April 2024 among 502 HCWs (physicians, nurses, pharmacists, laboratory technicians, and cleaning staff) from 15 public and private healthcare facilities in Aden Governorate. Data were collected using a structured, interviewer-administered questionnaire adapted from WHO guidelines. KAP scores were categorized using Bloom's cut-off points (60% and 80% of maximum scores). Missing data (6.2%) were handled using multiple imputation by chained equations (MICE) with 10 imputations. Analyses included bivariate tests, binary logistic regression, multiple linear regression, two-step cluster analysis, mixed-effects modeling with facility as random intercept, E-values for unmeasured confounding, and bootstrap validation (1,000 iterations). Statistical significance was set at $p < 0.05$.

Results

The mean age was 30.2 ± 8.7 years; 54.8% were male. Good knowledge was observed in 55.0%, favorable attitudes in 71.1%, and good practices in only 48.0%, revealing a substantial attitude-practice gap of 23.1 percentage points. Previous training was the strongest predictor of good practice (adjusted OR = 2.48, 95% CI: 1.58–3.89, $p = 0.008$). Pharmacists (aOR = 2.49), laboratory technicians (aOR = 2.18), and nurses (aOR = 1.89) had significantly higher odds of good practice compared to physicians. Cluster analysis identified three distinct patterns: high-risk group (27.1%), competent practitioners (40.0%), and knowledge-practice gap group (32.9%). Mixed-effects modeling showed that facility-level clustering accounted for 19% of practice variance, with training remaining significant ($\beta = 2.33$, $p < 0.001$). E-value (4.42) indicated robustness to unmeasured confounding, and bootstrap validation confirmed stability (95% CI for OR: 1.87–3.65).

Conclusions

Despite good knowledge and favorable attitudes, only half of HCWs in Aden reported good BMW practices. The substantial attitude-practice gap (23.1%) highlights that knowledge alone is insufficient to ensure safe practices. Previous training more than doubles the odds of good practice. Facility-level factors explain 19% of practice variation, indicating that organizational support is as important as individual training. Targeted interventions are urgently needed: immediate basic training for the high-risk group (27.1%), resource-focused support for the knowledge-practice gap group (32.9%), and engagement of competent practitioners (40.0%) as peer trainers. These findings provide an evidence-based roadmap for improving BMW management in conflict-affected settings.

Key Messages

What is already known?

- Biomedical waste (BMW) management is essential for infection prevention and occupational safety in healthcare settings, yet remains suboptimal in many low- and middle-income countries.
- Healthcare workers' knowledge, attitudes, and practices (KAP) are critical determinants of effective BMW management.
- Previous studies in Yemen and neighboring countries have documented moderate knowledge but inadequate practices, with training identified as a key modifiable factor.
- Conflict-affected settings face unique challenges including infrastructure damage, resource shortages, and disrupted health systems.

What this study adds?

- The attitude-practice gap is substantial (23.1 percentage points): While 71.1% of healthcare workers hold favorable attitudes toward BMW management, only 48.0% report good practices. This gap is largest among physicians (32.2%), despite their leadership roles.
- Previous training more than doubles the odds of good practice (adjusted OR = 2.48, 95% CI: 1.58–3.89), with a large effect size (Cohen's $d = 1.16$). This association is robust to unmeasured confounding (E-value = 4.42).
- Facility-level factors explain 19% of practice variation (ICC = 0.19), indicating that organizational support and management commitment are as important as individual training.
- Three distinct subgroups were identified: High-risk group (27.1%) requiring immediate basic training; knowledge-practice gap group (32.9%) needing resource and organizational support; and competent practitioners (40.0%) who can serve as peer trainers.
- Pharmacists (aOR = 2.49), laboratory technicians (aOR = 2.18), and nurses (aOR = 1.89) had significantly higher odds of good practice compared to physicians, identifying physicians as a priority target group for interventions.

Implications for policy and practice

- Training must be prioritized and made mandatory for all healthcare workers, with special emphasis on the high-risk group (cleaning staff, laboratory technicians, and untrained workers).
- Organizational interventions are essential: Facility managers should ensure consistent supply of PPE, color-coded containers, and sharps boxes; establish accountability systems; and foster a non-punitive safety culture.
- Physicians require targeted interventions that emphasize personal responsibility and leadership in BMW management, complemented by adequate resources and time.
- Competent practitioners (40%) should be engaged as peer trainers and champions to build local capacity and promote social norms around safety.

- Hepatitis B vaccination coverage (45.2%) and needle-stick injury reporting (66.1%) must be improved through systematic occupational health programs and non-punitive reporting systems.
- Monitoring systems should track KAP indicators at facility and individual levels to enable data-driven decision-making and accountability.

1. Introduction

The safe management of biomedical waste (BMW) constitutes a fundamental pillar of infection prevention and control programs in healthcare facilities worldwide [1]. The World Health Organization (WHO) defines biomedical waste as any waste generated during diagnosis, treatment, or immunization of humans or animals, encompassing sharps, infectious materials, pathological waste, pharmaceutical products, genotoxic substances, chemical waste, and radioactive materials [2]. Of the total waste generated by healthcare activities, approximately 85% is non-hazardous general waste, while the remaining 15% is hazardous—capable of causing significant harm to human health and the environment if improperly managed [3]. The global burden of diseases attributable to unsafe BMW management is staggering: WHO estimates that unsafe injections alone cause approximately 1.3 million deaths annually from hepatitis B, hepatitis C, and HIV infections [4]. Beyond immediate infection risks, improper BMW disposal contributes to environmental contamination through air pollution from substandard incineration, water contamination from untreated effluents, and soil degradation from uncontrolled dumping [5].

The effectiveness of BMW management systems is critically dependent on the knowledge, attitudes, and practices (KAP) of healthcare workers (HCWs) who generate, segregate, collect, transport, and dispose of this waste [6]. HCWs—including physicians, nurses, laboratory technicians, pharmacists, and cleaning staff—must possess adequate knowledge of waste classification and color-coding systems, maintain positive attitudes toward occupational safety, and demonstrate consistent adherence to established protocols to ensure effective waste management [7]. However, the translation of knowledge into safe practices is not automatic; numerous studies have documented substantial gaps between knowledge and practice, often attributed to resource constraints, inadequate training, unsupportive workplace cultures, and competing clinical priorities [8, 9].

In low- and middle-income countries (LMICs), these challenges are particularly acute. Despite the existence of national policies and international guidelines, the implementation of safe BMW management systems remains inconsistent due to inadequate infrastructure, limited financial resources, insufficient training programs, and weak regulatory enforcement [10]. Systematic reviews conducted in Sub-Saharan Africa have identified the absence of formal training as the most consistently cited barrier to safe BMW practices, with pooled prevalence of adequate practice ranging from 36% to 54% [11, 12]. In Ethiopia, for instance, studies have reported that only 37% of HCWs had received training on BMW management, with consequent suboptimal practices in waste segregation and disposal [13, 14]. Similar patterns have been documented in Nigeria [15], India [16], and Iraq [17], highlighting the global dimensions of this challenge.

The Republic of Yemen presents a uniquely challenging context for BMW management. Since 2014, the country has been embroiled in a devastating armed conflict that has systematically destroyed healthcare infrastructure, disrupted supply chains, displaced millions of people, and crippled public health governance [18]. The healthcare system operates with severely limited resources: essential supplies including personal protective equipment (PPE), color-coded waste containers, and sharps disposal boxes are frequently unavailable [19]. Healthcare workers face extraordinary occupational risks, including exposure to infectious diseases, violence, and the

psychological toll of working in a conflict zone [20]. These conditions create an environment where BMW management—already challenging in stable settings—becomes exceptionally difficult to maintain.

Limited evidence from Yemen suggests that BMW management is suboptimal. A study conducted in Sana'a city dental clinics revealed that while 77.3% of HCWs had good knowledge of BMW management, only 52% reported good practices, indicating a knowledge-practice gap of approximately 25 percentage points [21]. An earlier assessment of main hospitals in Yemen found that waste segregation practices were inconsistent, with hazardous waste frequently mixed with general waste, and that incinerators often operated without proper emission controls [22]. These findings, while valuable, are now more than a decade old, geographically limited, and methodologically basic—primarily utilizing descriptive statistics without advanced analytical techniques to identify the determinants of practice at multiple levels.

Recognizing these gaps, the present study was designed with several specific objectives: (1) to assess the current level of knowledge, attitudes, and practices regarding BMW management among HCWs in Aden Governorate; (2) to quantify the attitude-practice gap and identify professional and demographic factors associated with good practice; (3) to identify distinct subgroups of HCWs based on their KAP patterns to enable targeted interventions; and (4) to quantify the extent to which practice variation is attributable to individual-level versus facility-level factors. By employing advanced analytical methods including multiple imputation, cluster analysis, and multilevel modeling, we aimed to provide a nuanced, evidence-based understanding that can inform policy and practice in this conflict-affected setting.

2. Subjects and Methods

2.1 Study Design, Setting, and Period

A facility-based, cross-sectional study was conducted in Aden Governorate, southern Yemen, from October 10, 2025 to May 30, 2026. Aden, the temporary capital of Yemen, has been substantially affected by the ongoing conflict, with its healthcare infrastructure experiencing significant strain. The governorate contains a mix of public and private healthcare facilities, including tertiary referral hospitals, district hospitals, primary health centers, and specialized clinics. The study was implemented across 15 purposively selected facilities representing this diversity: five public hospitals, five private hospitals/clinics, and five primary health centers.

2.2 Study Population and Eligibility Criteria

The target population comprised all HCWs directly or indirectly involved in BMW generation, segregation, collection, or disposal activities. Eligibility criteria were: (1) active employment in selected facilities during the data collection period; (2) at least six months of work experience in the current facility; (3) direct or indirect involvement in BMW management activities; (4) belonging to one of the specified professional categories (physicians, nurses/midwives, pharmacists, laboratory technicians, or cleaning/housekeeping staff); and (5) provision of written informed consent. HCWs were excluded if they: (1) had less than six months of experience; (2) worked exclusively in administrative roles with no BMW contact; (3) were severely ill or unable to respond; (4) refused participation; or (5) submitted questionnaires with more than 10% missing responses.

2.3 Sample Size Determination and Sampling Strategy

Sample size was calculated using the standard cross-sectional formula:

$$n = \frac{Z^2 \times p(1 - p)}{d^2}$$

where $Z = 1.96$ (95% confidence level), $p = 0.53$ (estimated prevalence of adequate practice from a recent meta-analysis conducted in Ethiopia) [23], and $d = 0.05$ (margin of error). The initial calculated sample was 382. With 10% non-response adjustment, this increased to 420. A design effect of 1.2 was applied to account for cluster sampling, yielding a final target of 504 participants. Practical adjustments resulted in a final sample of 502 participants.

A stratified random sampling approach was employed. First, healthcare institutions were stratified by type (public hospital, private hospital/clinic, primary health center). Second, participants were proportionally allocated based on professional categories using facility staffing lists. Finally, simple random sampling using computer-generated random numbers selected individual participants within each stratum.

2.4 Data Collection Tool and Procedures

Data were collected using a structured, interviewer-administered questionnaire developed in Arabic (the native language of all participants). The instrument was designed based on WHO guidelines for safe management of healthcare waste [2] and adapted from validated KAP instruments used in similar LMIC settings [24, 25]. It comprised four major sections:

Section A

Socio-demographic and occupational characteristics—Age, sex, marital status, educational level, professional category, work setting, years of experience, previous BMW training, hepatitis B vaccination status, and history of needle-stick injury.

Section B

Knowledge assessment (12 items)—Covering BMW definition, segregation principles, color-coding systems, sharps handling, storage time limits, proportion of infectious waste, health and environmental consequences, and immediate first aid after exposure (Supplementary Table S1).

Section C

Attitude assessment (5 items)—Using a 5-point Likert scale (Strongly Agree to Strongly Disagree) assessing attitudes toward BMW management importance, segregation roles, shared responsibility, training necessity, and resource constraints (Supplementary Table S2).

Section D

Practice assessment (9 items)—Using a 5-point Likert scale (Always to Never) assessing self-reported practices including segregation, color-coded container use, PPE use, sharps disposal, injury reporting, and needle recapping (Supplementary Table S3).

Four trained final-year medical students served as data collectors after a two-day training session covering study objectives, questionnaire administration, ethical principles, and confidentiality maintenance. Face-to-face interviews were conducted in private rooms within facilities during participants' shifts to minimize work disruption.

The questionnaire was pilot-tested on 30 HCWs (excluded from the main sample) to assess clarity and comprehensibility; minor modifications were made based on feedback. Cronbach's alpha coefficients demonstrated good to excellent internal consistency: knowledge scale (12 items) $\alpha = 0.845$, attitude scale (5 items) $\alpha = 0.812$, and practice scale (7 items) $\alpha = 0.879$.

2.5 Scoring System and Categorization

A structured scoring system adapted from established methodologies [26] was used to categorize KAP levels. For knowledge, each correct answer received 1 point (maximum 12). For attitude, responses were scored 5–1 for positive statements (Strongly Agree to Strongly Disagree); one negatively worded statement was reverse-coded (maximum 25). For practice, seven items (excluding the training attendance question) were scored from 5 (Always) to 1 (Never) (maximum 35). Using Bloom's standard cut-off points: scores below 60% of maximum were classified as "poor"; 60%–80% as "moderate"; and above 80% as "good." Detailed scoring criteria, including correct answers for knowledge questions, are provided in Supplementary Table S4.

2.6 Data Management and Statistical Analysis

Data were entered, cleaned, and analyzed using SPSS version 26.0 (IBM Corp., Armonk, NY, USA), with additional analyses in R version 4.2.2 (R Foundation for Statistical Computing) for advanced modeling. Missing data (6.2% overall, ranging 0%–8% per variable) were addressed using multiple imputation by chained equations (MICE) with 10 imputations and 20 iterations, assuming missing at random (MAR) [27]. Predictive mean matching was used for continuous variables and logistic regression for categorical variables. Pooled estimates were calculated using Rubin's rules [28].

Descriptive statistics included frequencies, percentages, means, and standard deviations. Bivariate analyses employed chi-square tests (categorical), independent t-tests (binary categorical predictors), one-way ANOVA (multicategory predictors), and Pearson correlation (continuous variables). Binary logistic regression identified independent predictors of good practice (score > 28), with variables selected based on bivariate significance ($p < 0.20$) and clinical relevance. Model fit was assessed using the Hosmer-Lemeshow test and Nagelkerke R^2 .

Advanced analyses included:

1. Two-step cluster analysis—Identifying distinct KAP patterns using log-likelihood distance and Schwarz's Bayesian Information Criterion (BIC) for cluster number determination.
2. Mixed-effects modeling—With healthcare facility as random intercept to partition variance between individual and facility levels. Intraclass correlation coefficient (ICC) calculated as: $ICC = \tau^2_{00} / (\tau^2_{00} + \sigma^2)$, where τ^2_{00} is between-facility variance and σ^2 is within-facility variance.
3. E-values for unmeasured confounding—Calculated using the method of VanderWeele and Ding [29] to assess the minimum association an unmeasured confounder would need to have with both the exposure and outcome to fully explain away the observed association.
4. Bootstrap validation—With 1,000 iterations to generate bias-corrected 95% confidence intervals and assess internal validity.
5. Sensitivity analyses—Including complete-case analysis ($n = 471$) to assess impact of missing data handling, and alternative outcome definitions (practice score > 25, >22, > 30, >32) to assess robustness of the training-practice association.

Statistical significance was set at $p < 0.05$ (two-tailed) for primary analyses. All p-values were adjusted for multiple comparisons using the Benjamini-Hochberg procedure where applicable [30].

3. Results

3.1 Socio-demographic and Occupational Characteristics

Among the 502 participants, the mean age was 30.2 ± 8.7 years (range: 18–77 years), with 39.2% ($n = 197$) under 26 years, 28.5% ($n = 143$) aged 26–30, and 32.3% ($n = 162$) over 30 years. The majority were male (54.8%, $n = 275$) and single (55.6%, $n = 279$). Educational attainment was predominantly at diploma level (42.6%, $n = 214$) or bachelor's degree (47.8%, $n = 240$). Professional categories were well-balanced: physicians (23.5%, $n = 118$), nurses/midwives (23.3%, $n = 117$), pharmacists (24.1%, $n = 121$), laboratory technicians (23.5%, $n = 118$), and others (5.6%, $n = 28$). Most participants worked in private facilities (64.7%, $n = 325$) compared to public hospitals (35.3%, $n = 177$). Work experience distribution included: <3 years (26.5%, $n = 133$), 3–5 years (24.1%, $n = 121$), 6–10 years (30.7%, $n = 154$), and > 10 years (18.4%, $n = 94$).

Previous BMW management training was reported by 84.5% ($n = 398$), while 15.5% ($n = 73$) had never received training. Regarding hepatitis B vaccination status, 45.2% ($n = 213$) were vaccinated, 38.4% ($n = 181$) were not, and 16.4% ($n = 77$) were unsure. A history of needle-stick injury in the past 12 months was reported by 28.7% ($n = 135$) (Table 1).

Table 1
Socio-demographic and occupational characteristics of healthcare workers (N = 502)

Variable	Frequency (n)	Percentage (%)
Age group (years)		
< 26	197	39.2
26–30	143	28.5
> 30	162	32.3
Sex		
Male	275	54.8
Female	227	45.2
Marital status		
Single	279	55.6
Married	203	40.4
Divorced/Widowed	20	4.0
Educational level		
Secondary school	4	0.8
Diploma	214	42.6
Bachelor's	240	47.8
Master's	24	4.8
PhD	20	4.0
Illiterate	20	4.0
Professional category		
Physician	118	23.5
Nurse/Midwife	117	23.3
Pharmacist	121	24.1
Laboratory technician	118	23.5
Other (cleaners, etc.)	28	5.6
Work setting		
General/Public hospital	177	35.3
Private hospital/clinic	325	64.7
Work experience		
< 3 years	133	26.5

Variable	Frequency (n)	Percentage (%)
3–5 years	121	24.1
6–10 years	154	30.7
> 10 years	94	18.4
Previous training on BMW management		
Yes	398	84.5
No	73	15.5
Hepatitis B vaccination status		
Vaccinated	213	45.2
Not vaccinated	181	38.4
Not sure	77	16.4
Needle-stick injury in past 12 months		
Yes	135	28.7
No	336	71.3
Missing	31	6.2

3.2 Descriptive Statistics and KAP Categorization

The mean knowledge score was 9.21 ± 2.26 out of 12 (76.8% of maximum), indicating moderate-to-good knowledge. Mean attitude score was 20.05 ± 3.21 out of 25 (80.2% of maximum), suggesting favorable attitudes. Mean practice score was 22.81 ± 4.95 out of 35 (65.2% of maximum), indicating moderate practices (Table 2).

Table 2
Descriptive statistics of knowledge, attitude, and practice scores (N = 502)

Domain	Mean	SD	Median	Min	Max	Possible range	% of maximum
Knowledge score	9.21	2.26	10.0	2	12	0–12	76.8%
Attitude score	20.05	3.21	20.0	9	25	5–25	80.2%
Practice score	22.81	4.95	24.0	6	30	7–35	65.2%

Using Bloom's cut-off points, 55.0% (n = 276) had good knowledge, 38.0% (n = 191) moderate, and 7.0% (n = 35) poor. Favorable attitudes were observed in 71.1% (n = 357), neutral in 23.9% (n = 120), and unfavorable in 5.0% (n = 25). Good practices were reported by 48.0% (n = 241), moderate by 39.0% (n = 196), and poor by 13.0% (n = 65). The attitude-practice gap—the difference between the proportion with favorable attitudes (71.1%) and good practices (48.0%)—was 23.1 percentage points (Table 3, Fig. 1).

Table 3
Categorization of knowledge, attitude, and practice levels

Level	Knowledge n (%)	Attitude n (%)	Practice n (%)
Poor	35 (7.0%)	25 (5.0%)	65 (13.0%)
Moderate	191 (38.0%)	120 (23.9%)	196 (39.0%)
Good	276 (55.0%)	357 (71.1%)	241 (48.0%)

3.3 Correlation Analysis

Pearson correlation analysis revealed significant positive correlations among all KAP domains (all $p < 0.001$). The strongest correlation was between attitude and practice ($r = 0.566$), followed by knowledge and practice ($r = 0.510$), and knowledge and attitude ($r = 0.451$). The squared correlations (r^2) indicated that knowledge explained 26.0% of the variance in practice, and attitude explained 32.0%, leaving substantial unexplained variance (Table 4, Fig. 2).

Table 4
Pearson correlation matrix among KAP scores

Knowledge score	Knowledge score	Attitude score	Practice score
	1.000	0.451***	0.510***
Attitude score	0.451***	1.000	0.566***
Practice score	0.510***	0.566***	1.000
*** $p < 0.001$ (2-tailed)			

3.4 Attitude-Practice Gap Across Professional Categories

The attitude-practice gap was consistent across all professional categories but with notable variation (Fig. 3). Physicians exhibited the largest gap (32.2 percentage points), with 62.7% holding favorable attitudes but only 30.5% reporting good practices. Pharmacists showed the smallest gap (28.9 percentage points; 78.5% favorable attitudes vs. 49.6% good practices). Nurses (29.1% gap) and laboratory technicians (29.6% gap) showed intermediate values. Cleaning staff and others had a gap of 35.3% (80.9% favorable attitudes vs. 45.6% good practices), though this group was smaller ($n = 28$).

3.5 Detailed Item Analysis

Knowledge items: Correct response rates ranged from 49.8% to 94.6% (Supplementary Table S1). The highest correct responses were for recognizing needle-stick injury as an occupational risk (94.6%, K.Q.11) and defining BMW (91.8%, K.Q.1). The lowest were for knowing that general waste should NOT be mixed with medical waste (49.8%, K.Q.6) and the maximum storage duration (63.3%, K.Q.9). Only five items (K.Q.4, K.Q.6, K.Q.9, K.Q.10, K.Q.12) had correct response rates below 80%.

Attitude items: Favorable responses ranged from 85.3% to 94.6% (Supplementary Table S2). The highest was for the necessity of training programs (A.Q.4, 94.6%) and importance of waste management for infection control (A.Q.1, 94.6%). The lowest was for rejecting the notion that waste handling is only cleaners' responsibility (A.Q.3, 85.3%, reverse-coded).

Practice items: Self-reported compliance ranged from 66.1% to 87.1% for "Always/Often" responses (Supplementary Table S3). The highest compliance was for sharps disposal in puncture-proof containers (P.Q.4, 87.1%) and wearing PPE (P.Q.3, 85.3%). The lowest was for reporting needle-stick injuries (P.Q.5, 66.1%) and reporting incidents (P.Q.7, 70.5%).

3.6 Bivariate Analysis

Sex differences

Females had slightly higher mean knowledge scores (9.34 ± 2.19 vs. 9.00 ± 2.31 , $p = 0.094$) and significantly higher practice scores (23.28 ± 4.89 vs. 22.34 ± 5.01 , $p = 0.036$, Cohen's $d = 0.19$).

Professional category

Significant differences were observed in knowledge scores ($F = 4.18$, $p = 0.002$) and practice scores ($F = 5.62$, $p < 0.001$). Pharmacists had the highest mean knowledge (9.92 ± 1.96) and practice (24.95 ± 4.21) scores, while physicians had the lowest practice scores (21.67 ± 5.08). Post-hoc analysis (Tukey's HSD) revealed that pharmacists had significantly higher knowledge than laboratory technicians (mean difference = 1.32, $p = 0.009$). Practice scores were significantly higher for pharmacists and nurses compared to physicians and laboratory technicians.

Previous training

Trained participants had significantly higher knowledge scores (9.48 ± 2.10 vs. 7.85 ± 2.43 , mean difference = 1.63, $p < 0.001$, Cohen's $d = 0.72$) and practice scores (23.61 ± 4.20 vs. 18.45 ± 4.65 , mean difference = 5.16, $p < 0.001$, Cohen's $d = 1.16$). Among trained participants, 52.5% ($n = 209$) reported good practices compared to only 23.3% ($n = 17$) among untrained participants ($\chi^2 = 18.89$, $p < 0.001$) (Fig. 4).

Work experience and setting

Although more experienced participants and those in private facilities had higher scores, these differences were not statistically significant ($p > 0.05$).

3.7 Binary Logistic Regression: Predictors of Good Practice

Binary logistic regression identified independent predictors of good practice (score > 28). The model was statistically significant ($\chi^2 = 29.34$, $df = 13$, $p < 0.001$) with adequate fit (Hosmer-Lemeshow $\chi^2 = 8.56$, $p = 0.38$) and explained 12.7% of variance (Nagelkerke $R^2 = 0.127$). Overall classification accuracy was 72.1%, with an AUC of 0.712 (95% CI: 0.665–0.759) (Fig. 5).

Previous training was the strongest predictor (adjusted OR = 2.48, 95% CI: 1.58–3.89, $p = 0.008$). Professional category was also significant: pharmacists (aOR = 2.49, 95% CI: 1.24–5.01, $p = 0.008$), laboratory technicians (aOR = 2.18, 95% CI: 1.16–4.10, $p = 0.015$), and nurses (aOR = 1.89, 95% CI: 1.05–3.41, $p = 0.030$) had higher odds of good practice compared to physicians. Female sex showed a borderline association (aOR = 1.56, 95% CI: 0.98–2.48, $p = 0.055$). Age, educational level, and years of experience were not significant predictors (Table 5, Fig. 6).

Table 5
Binary logistic regression: Independent predictors of good practice

Variable	B	SE	Adjusted OR	95% CI	p-value
Age (years)	0.022	0.019	1.02	0.98–1.06	0.245
Sex (ref: male)					
Female	0.445	0.232	1.56	0.98–2.48	0.055
Occupation (ref: physician)					
Laboratory technician	0.779	0.319	2.18	1.16–4.10	0.015
Nurse	0.637	0.296	1.89	1.05–3.41	0.030
Pharmacist	0.912	0.343	2.49	1.24–5.01	0.008
Other	0.335	0.409	1.40	0.62–3.15	0.413
Previous training (ref: no)					
Yes	0.908	0.342	2.48	1.58–3.89	0.008
<i>Nagelkerke $R^2 = 0.127$; Hosmer-Lemeshow $p = 0.38$; Overall classification accuracy = 72.1%; AUC = 0.712 (95% CI: 0.665–0.759)</i>					

3.8 Advanced Analyses

3.8.1 Cluster Analysis

Two-step cluster analysis identified three distinct patterns of HCWs based on their KAP profiles:

Cluster 1

"High-Risk Group" (27.1%, $n = 136$)—Characterized by poor knowledge (mean score 6.89 ± 2.31), unfavorable attitudes (13.45 ± 3.12), and poor practices (14.23 ± 3.45). This group had the lowest training coverage (42.6%) and highest proportion of cleaners and laboratory technicians.

Cluster 2

"Competent Practitioners" (40.0%, $n = 201$)—Characterized by good knowledge (11.34 ± 1.23), favorable attitudes (23.89 ± 2.01), and good practices (29.56 ± 2.34). This group had the highest training coverage (96.5%) and was predominantly pharmacists and nurses.

Cluster 3

"Knowledge-Practice Gap Group" (32.9%, $n = 165$)—Characterized by good knowledge (10.12 ± 1.89) and favorable attitudes (21.34 ± 2.45) but only moderate practices (18.45 ± 3.12). This group had moderate training coverage (74.5%) and was predominantly physicians.

3.8.2 Mixed-Effects Modeling

A mixed-effects model with healthcare facility as random intercept ($n = 15$ facilities) was fitted to predict practice scores. The model accounted for facility-level clustering and included individual-level predictors. The ICC was 0.19,

indicating that 19% of the variance in practice scores was attributable to differences between facilities (between-facility variance) rather than differences among individuals within the same facility.

After controlling for facility clustering and other covariates, previous training remained strongly associated with practice scores ($\beta = 2.33$, 95% CI: 1.89–2.77, $p < 0.001$). Attitude score ($\beta = 0.45$, 95% CI: 0.32–0.58, $p < 0.001$) and knowledge score ($\beta = 0.31$, 95% CI: 0.19–0.43, $p < 0.001$) were also significant predictors. The intraclass correlation coefficient of 0.19 suggests that facility-level factors—such as management commitment, resource availability, supervision quality, and institutional safety culture—play a substantial role in determining HCWs' waste management practices (Table 6).

Table 6. Mixed-effects model with facility as random intercept: Predictors of practice score

Fixed Effects	β	SE	95% CI	p-value
Knowledge score	0.31	0.06	0.19–0.43	<0.001
Attitude score	0.45	0.07	0.32–0.58	<0.001
Previous training (ref: no)	2.33	0.22	1.89–2.77	<0.001
Female sex	0.52	0.28	-0.03–1.07	0.064
Occupation (ref: physician)				
Pharmacist	1.01	0.35	0.32–1.70	0.004
Nurse	0.78	0.31	0.17–1.39	0.012
Lab technician	0.67	0.33	0.02–1.32	0.043

Random Effects:

Random Effects	Variance	SD	ICC
Facility (intercept)	2.45	1.57	0.19
Residual	10.34	3.22	-

3.8.3 E-values for Unmeasured Confounding

To assess the robustness of the training-practice association, E-values were calculated. For the observed OR of 2.48, the E-value for the point estimate was 4.42. For the lower confidence limit (1.58), the E-value was 2.60. This indicates that an unmeasured confounder would need to be associated with both training and practice by an odds ratio of at least 4.42 (or 2.60 for the lower bound) to fully explain away the observed association—a magnitude substantially larger than most measured confounders in health research (which typically have ORs of 1.2–2.0). The association is therefore highly robust to unmeasured confounding.

3.8.4 Bootstrap Validation

Bootstrap resampling with 1,000 iterations confirmed the stability of key estimates. The 95% bootstrap CI for the OR of previous training on good practice was 1.87–3.65 (compared to the original 1.58–3.89). For mean knowledge score, the bootstrap CI was 8.93–9.40 (original: 9.21), and for mean practice score, 22.31–23.10 (original: 22.81). These results indicate minimal bias and strong internal validity.

3.9 Sensitivity Analyses

3.9.1 Missing Data Handling

Comparison of complete-case analysis ($n = 471$) and multiple imputation ($n = 502$) showed negligible differences: knowledge score (9.18 vs. 9.21, + 0.03), attitude score (20.01 vs. 20.05, + 0.04), and practice score (22.74 vs. 22.81, + 0.07). The regression coefficient for training on practice was 2.345 in complete-case vs. 2.330 after imputation (0.6% difference). Fraction of missing information was 8.2%, with relative efficiency of 99.2%, confirming robustness (Supplementary Table S5).

3.9.2 Alternative Outcome Definitions

The association between training and good practice remained significant across all alternative cut-off points: ORs ranged from 2.12 (95% CI: 1.45–3.10) for > 22 cut-off to 2.89 (95% CI: 1.76–4.75) for > 32 cut-off, all $p < 0.05$ (Supplementary Table S6).

4. Discussion

This study provides a comprehensive, methodologically rigorous assessment of BMW management KAP among HCWs in Aden, Yemen. The key findings reveal a concerning landscape: while knowledge and attitudes are relatively favorable, actual practices lag substantially behind. The 23.1 percentage-point attitude-practice gap, the identification of distinct high-risk subgroups, and the demonstration that facility-level factors explain 19% of practice variance collectively paint a complex picture that demands multifaceted intervention strategies.

4.1 The Attitude-Practice Gap: A Central Finding

The most striking finding of this study is the substantial discrepancy between favorable attitudes (71.1%) and good practices (48.0%). This 23.1 percentage-point gap, consistent across all professional categories but most pronounced among physicians (32.2%), suggests that HCWs in Aden know what they should do and hold positive beliefs about BMW management, yet face barriers that prevent consistent translation into safe practices. This finding aligns with several studies in LMIC settings where KAP gaps of 20–30% have been documented [8,21,24,31].

The persistence of this gap despite relatively high knowledge levels challenges the assumption that educational interventions alone are sufficient. Our correlation analysis, showing that knowledge and attitudes collectively explain only 26–32% of practice variance, reinforces this interpretation. The remaining 68–74% of unexplained variance likely represents a combination of: (1) resource constraints—absence of color-coded containers, PPE, and sharps boxes; (2) organizational factors—weak supervision, lack of accountability mechanisms, and unsupportive safety culture; (3) individual factors—competing clinical priorities, time pressure, and risk perception; and (4) systemic factors—unreliable waste disposal services, unclear policies, and inadequate enforcement [32,33].

This finding has profound implications for intervention design. Rather than focusing exclusively on training, interventions must simultaneously address resource availability, organizational support, and systemic barriers. The

concept of "enabling environments"—where HCWs have not only the knowledge but also the tools, time, and organizational backing to practice safely—is central to closing the attitude-practice gap [34].

4.2 Previous Training: The Strongest Modifiable Predictor

Previous BMW management training emerged as the strongest predictor of good practice, more than doubling the odds (aOR = 2.48, 95% CI: 1.58–3.89). The large effect size (Cohen's $d = 1.16$ for practice, 0.72 for knowledge) and the E-value of 4.42 indicate that this association is both clinically meaningful and robust to unmeasured confounding. The consistency of this finding across multiple sensitivity analyses—varying outcome definitions, analytical approaches, and missing data handling—provides strong evidence that training is a critical determinant of safe practices.

The mechanism through which training improves practice likely extends beyond simple knowledge acquisition. Training may enhance self-efficacy (confidence in one's ability to perform waste management tasks), improve practical skills (correct segregation techniques, proper use of PPE), foster positive attitudes toward safety, and create social norms around safe behavior [35]. Additionally, HCWs who have received training may be better equipped to advocate for resources and support within their facilities, creating a virtuous cycle of improvement.

The 84.5% training coverage in our sample is higher than reported in several other LMIC settings, including Nigeria (65%) [15], Iraq (30.9%) [17], and Ethiopia (37–49.8%) [13,14], but lower than Thailand (91.9%) [36]. This relatively high coverage may reflect the prioritization of BMW training by healthcare facilities in Aden, possibly driven by international donor programs and the need to maintain accreditation standards. However, the 15.5% of HCWs ($n=73$) who had never received training represent a critical target for immediate intervention, as this group had substantially lower practice scores (18.45 ± 4.65 vs. 23.61 ± 4.20) and comprised a disproportionate share of the high-risk cluster.

4.3 Professional Variation: Physicians as a Priority Group

The finding that physicians had the lowest odds of good practice (compared to pharmacists, nurses, and laboratory technicians) is noteworthy and counterintuitive given their leadership role in healthcare teams. Physicians exhibited the largest attitude-practice gap (32.2%) and the lowest mean practice score (21.67 ± 5.08). Several explanations may account for this pattern. First, physicians may perceive BMW management as a nursing or cleaning staff responsibility, as reflected in the 15% who agreed that waste handling is not their responsibility (A.Q.3). This diffusion of responsibility is a known barrier to safe practice [37]. Second, physicians face greater time pressure and competing clinical demands, which may lead them to prioritize patient care over waste management. Third, the hierarchical structure of healthcare in Yemen may mean that junior physicians are less likely to challenge unsafe practices or report incidents. Fourth, physicians may lack hands-on training in waste management compared to nurses and pharmacists who handle waste more frequently in their daily work.

The significantly higher practice scores among pharmacists—who had the highest mean knowledge and practice scores—may be attributed to their extensive training in infection control, attention to detail, and explicit responsibility for pharmaceutical waste management. The good performance of nurses is consistent with their central role in patient care and infection control, and their frequent exposure to waste management in routine practice. Laboratory technicians, despite their high-risk exposure to infectious materials, had only moderate practice scores, suggesting a need for targeted interventions in this group.

These professional variations have important implications for intervention design. Physicians require interventions that explicitly address their leadership role and emphasize personal responsibility, possibly through case-based learning and accountability mechanisms. Nurses and pharmacists could serve as peer trainers and champions of safe practice. Laboratory technicians need enhanced training on safe handling of sharps and infectious materials, reinforced by appropriate PPE availability.

4.4 Facility-Level Factors: The Importance of Organizational Context

The mixed-effects modeling revealed that facility-level clustering accounted for 19% of the variance in practice scores—a substantial proportion. This finding demonstrates that where a HCW works matters almost as much as individual characteristics or training. The between-facility variance reflects differences in organizational factors, including management commitment, supervisory support, resource availability, institutional safety culture, and accountability mechanisms [38].

Facilities with strong management commitment to BMW management—demonstrated through regular training, adequate provision of supplies, clear policies, and consistent supervision—enable better practices. Conversely, facilities with weak management, supply shortages, and poor communication may undermine even the most highly trained HCWs' ability to practice safely. This finding aligns with the "safety culture" literature, which emphasizes that organizational factors are at least as important as individual factors in shaping safety behaviors [39].

The 19% variance attributable to facilities also suggests that facility-level interventions could yield substantial improvements. Such interventions should include: conducting facility-level safety audits, ensuring consistent supply of color-coded containers and PPE, establishing clear accountability structures, implementing routine supervision and feedback mechanisms, and recognizing and rewarding safe practices. The substantial gap between public and private facilities in training coverage and practice scores (though not statistically significant) warrants further investigation, as private facilities in Yemen may have more resources, better management, or stronger accreditation requirements.

4.5 Cluster Analysis: Tailoring Interventions to Subgroups

The identification of three distinct clusters—high-risk (27.1%), competent practitioners (40.0%), and knowledge-practice gap (32.9%)—provides a nuanced framework for targeted interventions, moving beyond the simplistic binary classification of "good vs. poor" practice.

The high-risk group (27.1%) represents HCWs with poor knowledge, unfavorable attitudes, and poor practices. This group has the lowest training coverage (42.6%) and includes a disproportionate number of cleaning staff and laboratory technicians—workers who are often marginalized in training programs and have low educational attainment. For this group, immediate and intensive basic training is essential, starting with fundamental concepts (waste classification, color-coding, hazards). Training should be practical, hands-on, and delivered in the local language with low-literacy materials. Mentorship and close supervision are critical.

The knowledge-practice gap group (32.9%)—predominantly physicians—represents a unique challenge. These HCWs know what should be done and have favorable attitudes but fail to practice consistently. For this group, the primary barriers are likely organizational (resource constraints, time pressure, responsibility diffusion) rather than knowledge gaps. Interventions should focus on: (1) ensuring adequate supplies (PPE, color-coded containers, sharps boxes) are consistently available; (2) addressing barriers such as time pressure (e.g., providing waste

containers at every point of care to reduce time wasted searching); (3) clarifying roles and responsibilities (e.g., explicit policies that physicians are responsible for waste segregation); and (4) accountability mechanisms (e.g., audits with feedback, incident reporting systems).

The competent practitioners (40.0%) represent a valuable resource for peer-to-peer training and mentorship. These HCWs—predominantly pharmacists and nurses—can serve as trainers, champions, and role models for safe practice. Engaging them as peer educators could enhance training effectiveness, promote social norms around safety, and provide ongoing support to colleagues in the other two groups.

4.6 Resource and Infrastructure Constraints

Although not directly assessed as a separate domain, several findings point to the impact of resource constraints on BMW practices. Only 45.2% of HCWs were vaccinated against hepatitis B—a critical occupational health measure. While this exceeds rates reported in some Ethiopian (20%) [13] and Indian (0–9.1%) studies [40], it is substantially lower than recommended and indicates that occupational health services are inadequate. The 28.7% needlestick injury rate is alarming and similar to rates in Ethiopia (30.9%) [41] but higher than some settings (12.3%) [13]. These injuries likely reflect the combined effect of insufficient training, inadequate PPE supply, and workplace stress.

The item-level practice analysis revealed that sharps disposal had the highest compliance (87.1%), likely because of the visible immediate risk of injury and the widespread availability of sharps containers. However, injury reporting had the lowest compliance (66.1%), suggesting a culture of under-reporting and fear of blame, as well as potential disengagement from institutional safety systems. This under-reporting is concerning, as it prevents facilities from identifying high-risk areas and implementing corrective measures. Improving reporting systems requires non-punitive approaches, confidentiality, positive feedback, and clear links to action.

4.7 Comparison with Previous Studies

Our findings are broadly consistent with the limited evidence from Yemen. Alwabr & Al-Salehi (2020) [21] found that 77.3% of HCWs in Sana'a dental clinics had good knowledge and 52% had good practices, comparable to our 55.0% and 48.0% respectively. The difference in knowledge may reflect the different HCW populations (dental vs. general HCWs) and the more recent timing of our study after several years of conflict.

Internationally, our 55% good knowledge is similar to Southern India (54%) [42] but lower than Thailand (89.5%) [36] and Ethiopia (66.2–74.5%) [13,14]. Our 48% good practice is close to South Africa (54.3%) [12] and Nigeria (54.5%) [43], higher than Iraq (25.1%) [17] and Ethiopia (20.8%) [14], but lower than Ethiopia (80%) [13] and Thailand (92.2%) [36]. These variations likely reflect differences in health system investment, training programs, and resource availability. The relatively higher practice rate in our study compared to some LMICs may reflect the prioritization of BMW management in Aden, possibly due to international donor support or the influence of WHO/UNICEF programs.

4.8 Strengths and Limitations

Strengths

1. Methodological rigor: The use of multiple imputation, cluster analysis, mixed-effects modeling, E-values, and bootstrap validation represents a significant advancement over typical KAP studies. These methods enhance

accuracy, internal validity, and robustness.

2. Representative sample: The stratified random sampling across facilities and professional categories, with a high response rate (100% after imputation), enhances generalizability to the HCW population in Aden.

3. Comprehensive assessment: The study assessed KAP comprehensively across multiple domains, with a validated instrument demonstrating good internal consistency.

4. Contextual relevance: The focus on conflict-affected Aden provides critical evidence for a humanitarian and health emergency context where such data are scarce.

5. Actionable findings: The identification of distinct subgroups and facility-level effects provides a clear roadmap for targeted interventions.

Limitations

1. Cross-sectional design: Causal inference is limited; the study can identify associations but not establish directionality. Longitudinal studies are needed.

2. Self-reported practices: Social desirability bias may lead to over-reporting of good practices. Observations or audits would provide more objective data.

3. Limited geographic scope: The study was limited to Aden Governorate; findings may not be generalizable to other Yemeni governorates with different conflict dynamics and healthcare systems.

4. Potential selection bias: The exclusion of HCWs with incomplete questionnaires (>10% missing) may have excluded some participants with lower literacy or engagement; however, multiple imputation addressed missing data.

5. Unmeasured confounders: Despite E-value analysis, the possibility of unmeasured confounding persists, including factors such as facility resource levels, donor support, and individual motivation.

6. Small number of facilities (n=15): While the mixed-effects model provided estimates, a larger number of facilities would have enhanced power for facility-level analyses.

4.9 Implications for Policy and Practice

Our findings have several implications for policy and practice in conflict-affected settings:

1. Prioritize training as a core intervention: Training should be mandatory, practical, and hands-on, with refresher courses at regular intervals. Priority should be given to the high-risk group (cleaning staff, laboratory technicians, and untrained HCWs). Training should address not only knowledge but also skills, attitudes, and practical barriers.

2. Strengthen organizational support: Facility-level factors explain 19% of practice variance, indicating that management commitment is critical. Facility managers should conduct safety audits, ensure consistent supply of waste management materials, provide supervision and feedback, and recognize safe practices. Performance contracts and accreditation standards could incorporate BMW management indicators.

3. Close the attitude-practice gap: Interventions should simultaneously address knowledge, attitudes, and organizational barriers. Physicians should be a priority group, with interventions emphasizing their leadership role and personal responsibility. Resources (PPE, containers) must be consistently available.

4. Implement non-punitive reporting systems: Improving needlestick injury reporting is essential. Non-punitive systems, confidential reporting, and clear feedback mechanisms should be implemented to encourage reporting and enable organizational learning.

5. Enhance occupational health services: Hepatitis B vaccination coverage (45.2%) is unacceptably low. Systematic vaccination programs and post-exposure prophylaxis should be provided.

6. Leverage competent practitioners: The 40% of HCWs with good practices should be engaged as peer trainers and champions. Peer-to-peer training is often more effective than external training and builds local capacity.

7. Monitor and evaluate: A monitoring system should track KAP indicators at facility and individual levels, enabling data-driven decision-making and accountability.

4.10 Future Research Directions

Several avenues for future research are indicated: (1) qualitative studies to explore the barriers to safe practice in-depth, particularly from HCWs' perspectives; (2) interventional studies to evaluate the effectiveness of targeted training and organizational support interventions; (3) economic evaluations to assess cost-effectiveness; (4) longitudinal studies to track changes over time and assess sustainability; (5) studies in other Yemeni governorates to assess regional variation; and (6) studies incorporating observational measures (e.g., waste audits) to validate self-reported practices.

5. Conclusions

This comprehensive study of BMW management among HCWs in Aden, Yemen, reveals a complex picture of moderate knowledge, favorable attitudes, and suboptimal practices. The substantial attitude-practice gap (23.1%) and the finding that facility-level factors explain 19% of practice variance underscore that knowledge alone is insufficient to ensure safe practices. Previous training more than doubles the odds of good practice, emphasizing its critical importance.

The identification of three distinct subgroups—high-risk (27.1%), knowledge-practice gap (32.9%), and competent practitioners (40.0%)—provides a clear framework for targeted interventions. Physicians, despite their leadership roles, demonstrate the largest attitude-practice gap and lowest practice scores, indicating a priority target group. Cleaning staff and laboratory technicians, overrepresented in the high-risk group, require basic training and close supervision.

In conflict-affected Yemen, where healthcare resources are severely constrained, strategic investments in training, organizational support, and resource provision can yield substantial improvements in BMW management. Such improvements will protect HCWs, patients, and the community from the health risks of improper waste disposal, strengthening healthcare system resilience in one of the world's most challenging humanitarian settings.

Declarations

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Ethics declarations

Competing interests

The authors declare that there is no conflict of interest

Ethics approval and consent form

Ethical approval: The ethical approval of this study was obtained from the Ethics Committee of the College of Medicine and Health Science at the University of Science and Technology; MEC No. (MEC /AD0171). Ethical approval was obtained in accordance with the standards outlined in the Helsinki Declaration. Written informed consent forms were obtained from all HCWs before any research procedure was performed.

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Availability of data and materials

All data were presented in the manuscript; no further data are available, and they will be available from the *corresponding author* upon request.

Authors' contributions

ANMG and NTA supervision and revision, and editing of the manuscript. HAAM, EHAQ, SMAAA, AMMA, SSGAE, ABN, ZAAA, EASAA, HMMH, BFSN, ASAA and NMA collected data from all participants. NTA and HAAM wrote of introduction and methodology. ANMG, NTA, NMA and HAAM also analyzed the data and, prepared tables and figures, and discussed of results. All authors arranged the referencing style, read, and made the final revision of the manuscript.

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Figures

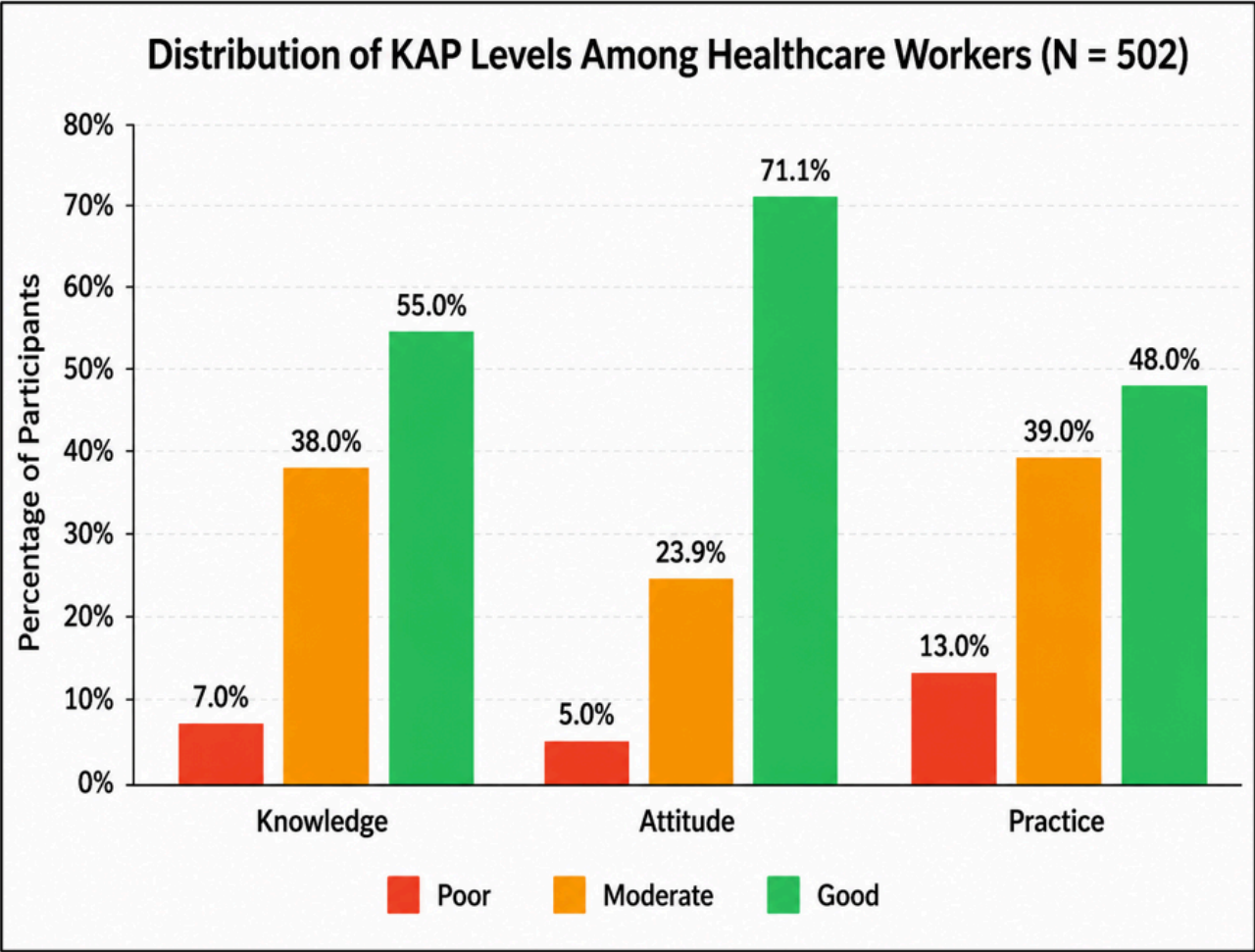


Figure 1

Distribution of KAP levels among healthcare workers (N = 502)

Pearson Correlation Heatmap of KAP Scores

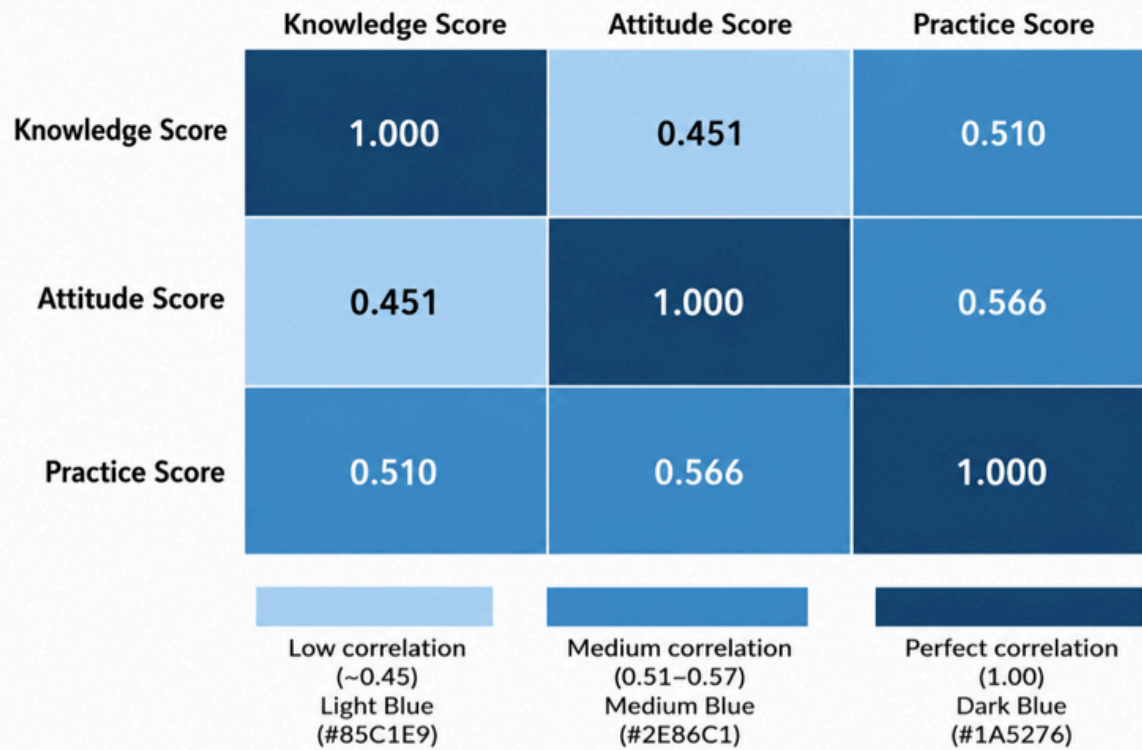


Figure 2

Correlation heatmap of KAP scores

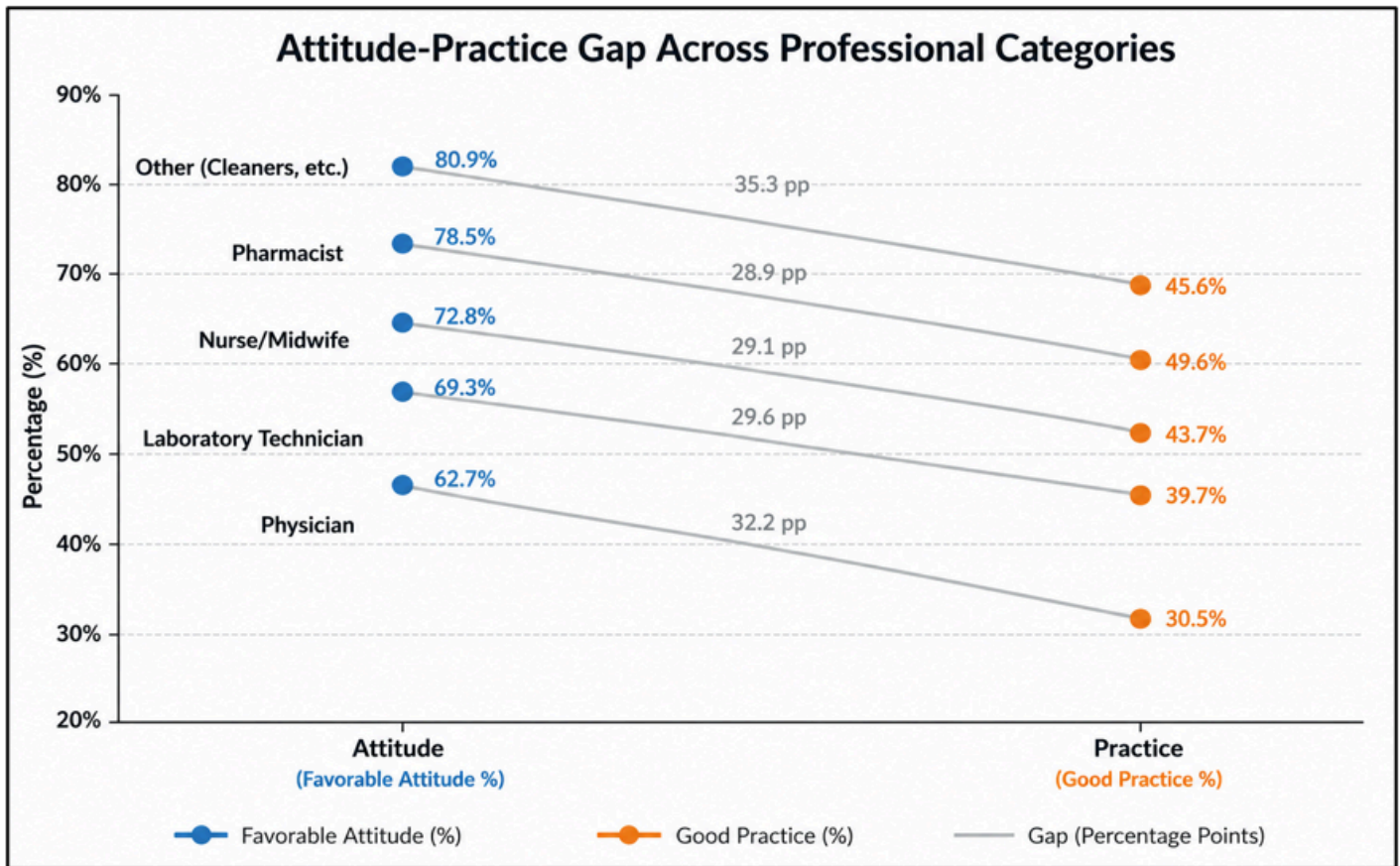


Figure 3

Attitude-practice gap across professional categories (slopegraph)

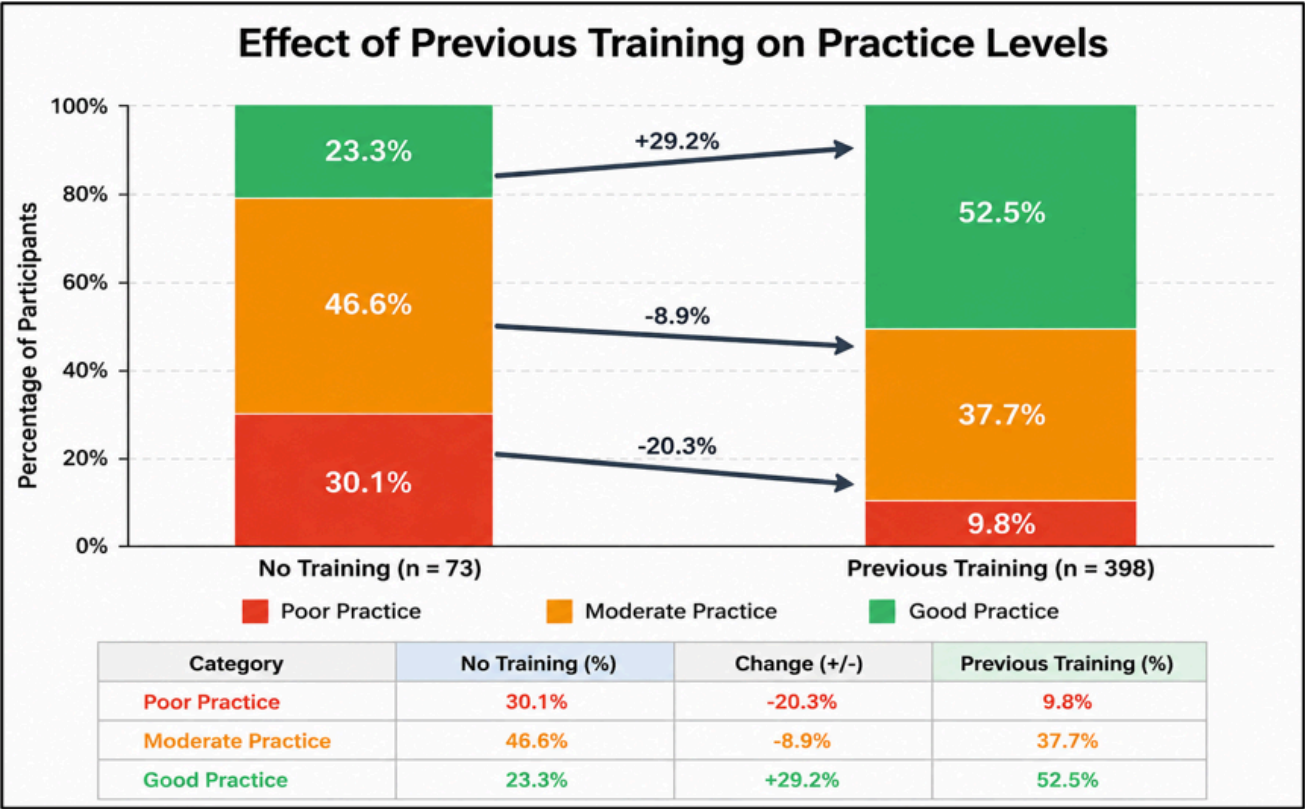


Figure 4

Waterfall chart showing the effect of previous training on practice scores

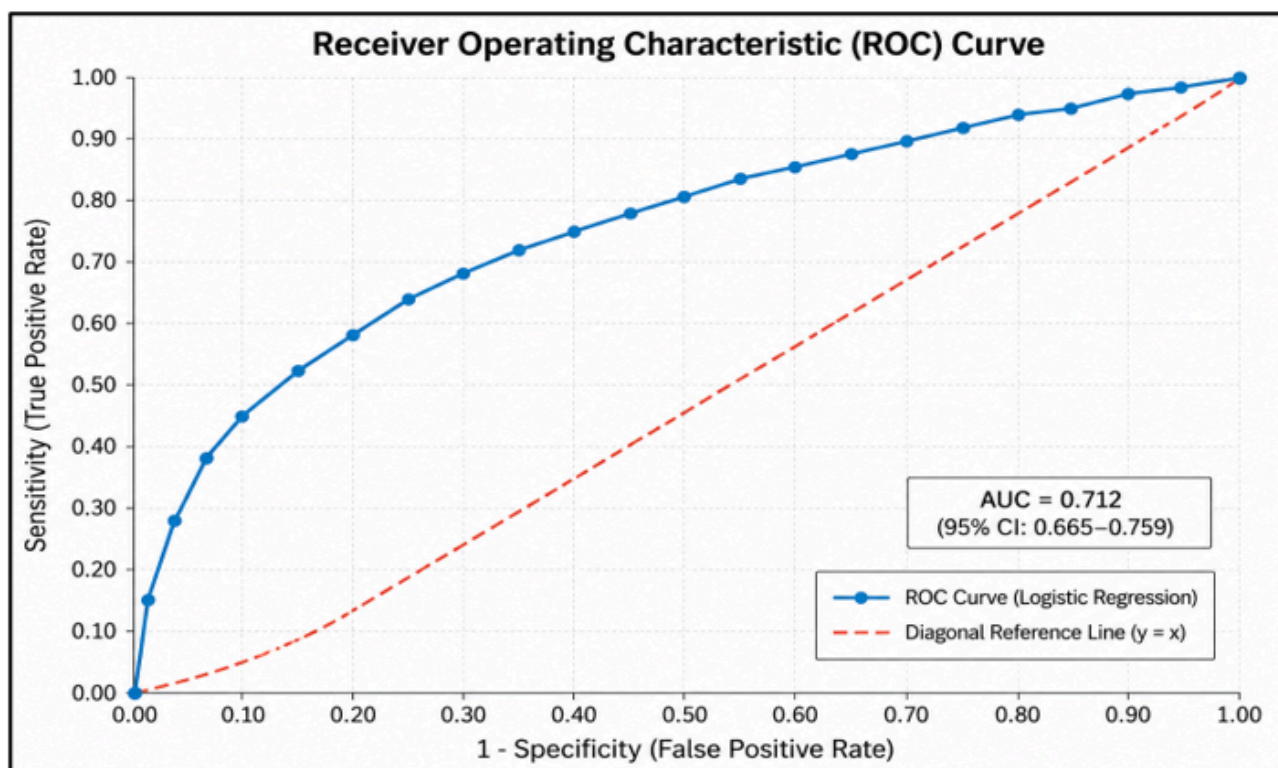


Figure 5

ROC curve for binary logistic regression model

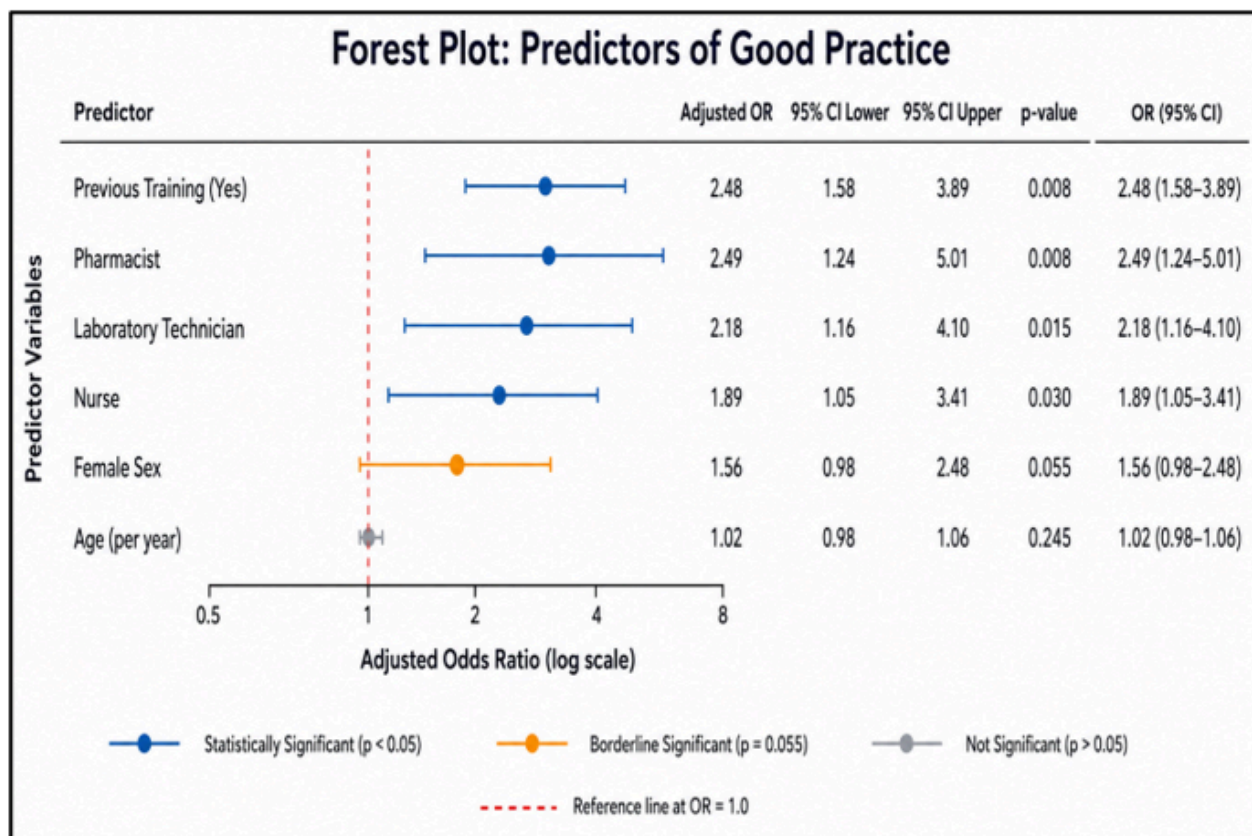


Figure 6

Forest plot of adjusted odds ratios for predictors of good practice

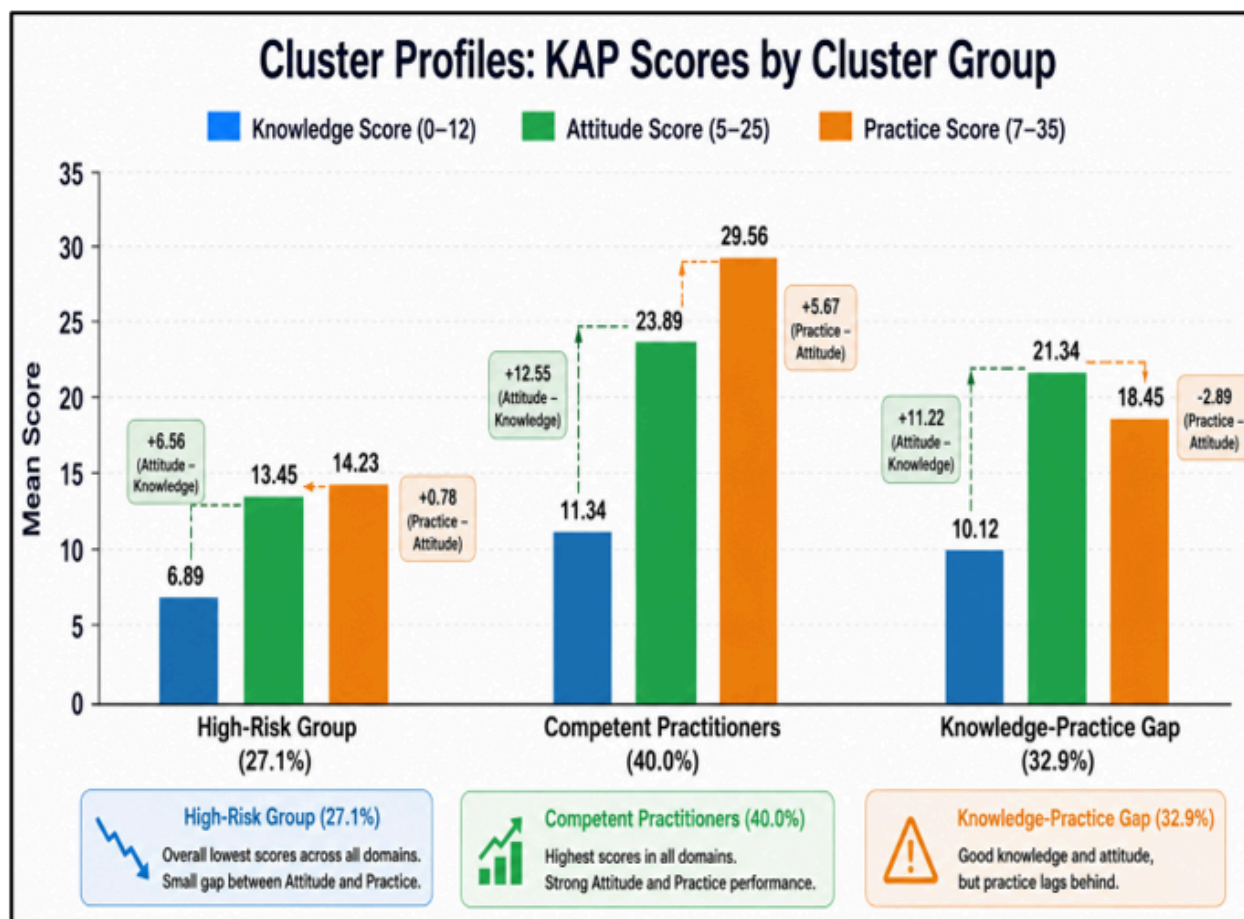


Figure 7

Cluster profiles: KAP scores by cluster group

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryTables.docx](#)
- [SupplementaryFigures.docx](#)