

Refrigeration and Air-Conditioning Equipment Users in Togo: A Cross-Sectional Assessment of Refrigerant Knowledge, Traceability, and Composition-Based Environmental Indicators.

Abstract:

Background and Objective: The rapid expansion of refrigeration and air-conditioning equipment in Sub-Saharan Africa raises environmental and occupational health concerns because of the continued use of refrigerants with high global warming potential (GWP) and, for some substances, ozone depletion potential (ODP). However, empirical data on users' knowledge and refrigerant traceability remain limited. This study aimed to assess refrigerant knowledge among equipment users in Togo, identify factors associated with knowledge levels, and characterise refrigerant composition and composition-based environmental indicators. Materials and Methods: This cross-sectional study surveyed 634 users across 10 cities in Togo using a structured questionnaire administered through KoboCollect. A spatial grid approach generated 60 cells, of which 45 were selected and 34 were effectively surveyed. Knowledge was assessed using a six-level ordinal scale and rescaled to 0–100. Statistical analyses included Mann–Whitney U, Kruskal–Wallis, one-way ANOVA, principal component analysis, and multiple linear regression with HC3 heteroscedasticity-consistent standard errors. Results: Knowledge was limited: 67.4% of air-conditioning users and 74.0% of refrigerator users could not identify the refrigerant in their equipment. The rescaled knowledge distributions were concentrated at the lowest levels. The first two PCA components explained 76.43% of the variance, while technical profession ($\beta = 11.74$, $p < 0.001$), training level ($\beta = 8.19$, $p < 0.001$), and age ($\beta = 0.434$, $p < 0.001$) were positively associated with the knowledge score (OLS $R^2 = 0.412$). Among refrigerators, R-134a was the most frequently identified refrigerant (15.30% of the total study population), whereas R-22 remained present in 6.20% of air conditioners. For air conditioners, the composition-based Environmental Pressure Index (EPI) was 0.164377, with R-410A contributing 37.3% of the index; R-22 accounted for all observed ozone-depletion pressure. Conclusion: The findings demonstrate substantial gaps in refrigerant knowledge and traceability among equipment users in Togo. The results support improved technical training, equipment labelling, refrigerant traceability, and enforcement of existing refrigerant-management requirements.

Keywords: Refrigerants; Hydrofluorocarbons; Hydrochlorofluorocarbons; Togo; Montreal Protocol.

1. Introduction

The refrigeration and air-conditioning sector is experiencing rapid growth in sub-Saharan Africa, driven by accelerated urbanization, rising demand for thermal comfort, demographic expansion, gradual improvement in living standards, and the intensification of heat episodes associated with climate change (IEA, 2018; UNEP, 2022). In Togo, as in many sub Saharan Africa countries, this dynamic has led to a substantial increase in the number of refrigeration and air-conditioning installations across residential, commercial, and institutional sectors. This expansion is accompanied by a significant rise in equipment operating primarily with chlorodifluoromethane (HCFC-22, R-22) and 1,1,1,2-tetrafluoroethane (HFC-134a, R-134a), both of which are greenhouse gases (GHGs) with well-documented environmental impacts (Myhre et al., 2013; Velders et al., 2015).

HCFC-22 possesses an ozone depletion potential (ODP) of 0.055 and a global warming potential (GWP) of 1810 over a 100-year horizon, placing it among the controlled substances under the Montreal Protocol. The Kigali Amendment applies to HFCs and established differentiated HFC phase-down schedules for Parties to the Montreal Protocol (UNEP, 2016). HFC-134a, although non-ozone-depleting (ODP = 0), has a GWP₁₀₀ of 1,430 (UNEP, 2023). The Kigali Amendment, adopted in 2016, established differentiated HFC phase-down schedules, including an 80% reduction from baseline by 2045 for Article 5 Group 1 Parties and an 85% reduction by 2047 for Article 5 Group 2 Parties (UNEP, 2016). Despite these international regulatory frameworks, compliance and enforcement remain uneven in some countries, where outdated equipment continues to operate and refrigerant management practices are poorly documented (Andersen and Sarma, 2012; UNEP DTIE OzonAction, 2019).

Cooling appliances are widely used in households, businesses, health facilities, hotels, and public institutions, yet empirical data on refrigerant-use practices in Sub-Saharan Africa remain limited. Key gaps include poor equipment traceability, continued use of obsolete refrigerants in informal markets, and low user awareness of the substances contained in their appliances (Andersen and Sarma, 2012; Velders et al., 2014). Inadequate knowledge and insufficient technician training may increase occupational exposure to refrigerants during accidental releases, particularly in confined spaces, while leaks of high-GWP refrigerants contribute to greenhouse-gas emissions

(Calm, 1996; Anders, 1991; Campbell et al., 1986). In Togo, there is a need to evaluate users' knowledge about refrigerant, characterize socio-occupational profiles, and identify factors associated with knowledge levels. Such evidence is essential for targeted training, risk identification, and effective environmental and public-health interventions (NRC, 1983; USEPA, 2011).

The present study was designed to address this gap by characterising refrigerant knowledge, traceability and composition among refrigeration and air-conditioning equipment users in Togo. Specifically, the objectives were: (1) to assess refrigerant knowledge among users of refrigerators and air conditioners; (2) to characterise refrigerants reported in current use and their GWP100 and ODP values; (3) to determine sociodemographic and professional factors associated with knowledge scores; and (4) to quantify composition-based traceability and environmental indicators for the refrigerants identified in air conditioners.

2. Materials and methods

2.1. Study design and setting

A cross-sectional descriptive and analytical study was conducted in 2024 across 10 cities in Togo: the Autonomous District of Grand Lomé (DAGL) and nine remote area cities (Kara, Dapaong, Sokodé, Atakpamé, Kpalimé, Tsévié, Mango, Notsé, and Aného). The nine interior cities were selected by simple random draw. The study setting is characterized by a tropical climate with temperatures frequently exceeding 30 °C, contributing to high demand for cooling equipment (Agence Nationale de la Météorologie du Togo, 2023).

2.2. Sampling strategy

A grid-based spatial sampling design was employed. Sixty cells (grids) were generated across the study area and numbered for selection, of which 45 were retained to ensure geographic coverage (Cochran, 1977). In DAGL, 15 of 25 cells were surveyed; in the remaining cities, 2 or 3 cells were surveyed (Table 1). Data collection involved visiting selected sampling locations starting from an accessible point within each grid. The nine interior cities were selected by simple random draw; within the selected cells, field recruitment followed the survey protocol. This design provided spatial coverage but should not be interpreted as simple random sampling of individual participants.

Table 1. Number of selected and surveyed grid cells by locality

Localités	Nombre total de mailles sélectionnées	Nombre de mailles enquêtées
DAGL	25	15
Kara	3	3
Kpalimé	3	2
Dapaong	2	2
Atakpamé	2	2
Sokodé	2	2
Tsévié	2	2
Aného	2	2
Notsé	2	2
Mango	2	2
Total	45	34

DAGL:Autonomous District of Greater Lomé

2.3. Sample size determination

The required sample size was calculated using Cochran's formula for proportions with a finite population correction. The parameters were: $z = 1.96$ (95% confidence level), $p = 0.5$ (maximum uncertainty proportion), and $e = 0.04$ (4% margin of error). The initial theoretical sample size was $n_0 = 600.25$. Adjusting for the total population of $N = 8,095,498$ (RGPH-5, 2023), the corrected sample size was $n = 600.2$. To ensure adequate precision while respecting the grid allocation, a final target sample size of $n = 652$ was adopted. A sensitivity analysis across margins of error (3.8–4.0%) gave theoretical sample sizes ranging from approximately 600 to 670. Of the 652 targeted participants, 634 completed the survey (response rate: 97.2%). The 18 non-respondents were distributed across seven sampling cells and comprised nine individuals who declined participation and nine who provided incomplete responses subsequently excluded during data quality checks. No formal non-response bias analysis was performed.

2.4. Data collection

Data were collected using a structured questionnaire administered electronically through the KoboCollect application (KoboToolbox, 2024), an open-source mobile survey platform widely validated in humanitarian and public health research (Aryalet al., 2023; Hartunget al., 2010). The questionnaire was developed based on a literature review of refrigerants and environmental knowledge, adapted from the interim report framework of the U.S. Environmental Protection

Agency (EPA, 1990). A pre-survey involving 30 participants, who were excluded from the main study, was conducted to assess item comprehension and estimate the average administration time.

2.5. Knowledge assessment framework

Knowledge was assessed on a six-level ordinal scale (0–5) adapted from the revised Bloom's taxonomy of cognitive domains (Bloom et al., 1956; Anderson and Krathwohl, 2001). The levels were defined as follows: Level 0 (No knowledge) corresponds to a complete absence of information on refrigerant use. Level 1 (Very weak) reflects minimal awareness of refrigerant use but an inability to differentiate basic concepts. Level 2 (Weak) indicates superficial and limited knowledge with no understanding of environmental and health impacts. Level 3 (Passable) represents a general but incomplete understanding, with errors on important details. Level 4 (Good) denotes the ability to recognize refrigerant names, common uses, and potential health and environmental effects. Level 5 (Very good) corresponds to comprehensive knowledge of physicochemical properties, equipment operation, safety, and energy efficiency. Ordinal levels were converted to a 100-point continuous scale using the linear transformation: $\text{Score} = (\text{Level} / 5) \times 100$, yielding possible values of 0, 20, 40, 60, 80, and 100. Proportions were estimated based on the number of favorable or unfavorable responses at each level.

2.6. Statistical analysis

Categorical variables were described by absolute and relative frequencies. Quantitative variables (age, knowledge score, equipment use duration) were summarized using mean, median, standard deviation, and range. Proportions were reported with 95% confidence intervals calculated using the Clopper–Pearson exact method (Clopper and Pearson, 1934).

Differences in equipment use duration across professional categories were assessed by one-way ANOVA, preceded by Levene's test for homogeneity of variances. Given the non-normal distribution of the knowledge score (Shapiro–Wilk, $p < 0.001$), sex-based comparisons of the knowledge score were performed using the Mann–Whitney U test rather than the parametric t-test. The non-parametric Kruskal–Wallis test was used for multi-group comparisons of the knowledge score (Kruskal and Wallis, 1952). Because no post-hoc pairwise results are reported in the present dataset, statistically significant omnibus tests are interpreted as evidence of overall between-group differences rather than as evidence for specific pairwise contrasts. The significance threshold was set at $\alpha = 0.05$.

Principal component analysis (PCA) was conducted on four coded participant characteristics: age (X_1), technical profession (X_2 , dichotomous 0/1), training level (X_3 , ordinal 1–4), and non-technical profession (X_4 , dichotomous 0/1), to explore multivariate structure and reduce dimensionality (Jolliffe, 2002). Because the variables were not all continuous, the PCA was considered exploratory rather than a formal latent-variable measurement model. Raw components were retained without Varimax rotation. The final R analysis showed that the first two components explained 76.43% of total variance (PC1 = 50.26%; PC2 = 26.16%).

A multiple linear regression model with HC3 heteroscedasticity-consistent standard errors was fitted to examine associations between the knowledge score and identified determinants. Heteroscedasticity was confirmed by three concordant tests: Breusch–Pagan (LM = 12.47, $p = 0.006$), White (statistic = 18.32, $p = 0.031$), and Goldfeld–Quandt ($F = 1.34$, $p = 0.041$). HC3 corrections were applied to ensure coefficient reliability (Long and Ervin, 2000; MacKinnon and White, 1985). The reported coefficient of determination is the ordinary least squares (OLS) R^2 , which represents the proportion of variance explained by the linear predictor under the standard OLS fit. While HC3 adjusts the standard errors for heteroscedasticity, the point estimates and hence the OLS R^2 remain unchanged; the R^2 value is therefore directly comparable to standard OLS R^2 values reported in the literature.

Finally, to quantify the information gap concerning refrigerant identification and its composition-based environmental context, a Refrigerant Traceability–Environmental Indicator Framework was applied. The framework integrates established environmental metrics, namely global warming potential (GWP_{100}) and ozone depletion potential (ODP), with a traceability measure and a normalised Shannon entropy. GWP_{100} and ODP are established environmental descriptors for characterising refrigerants according to their climate and ozone-layer impacts. The GWP_{100} values used in this study correspond to the IPCC AR4 basis used consistently across the refrigerants listed in the tables. In particular, the environmental performance of refrigerants is increasingly assessed using both GWP and ODP, alongside other thermodynamic and safety characteristics, when evaluating alternatives for refrigeration and air-conditioning applications (Tan and Erişen, 2026; Yang et al., 2021). The mathematical framework therefore enabled the information gap regarding refrigerant identification to be quantified and interpreted in relation to the environmental relevance and compositional heterogeneity of the refrigerants. Four complementary indicators were defined: the Traceability Index (T), the Environmental Pressure Index (EPI), the Ozone-Depletion Pressure Index (ODP_I), and the

normalised Shannon entropy (H_{N}). The Shannon entropy component was derived from the information-theoretic framework introduced by Shannon (1948) and its subsequent application to quantify distributional heterogeneity and diversity (Jost, 2006). All analyses were conducted using R (version 4.6.0; R Core Team, 2026).

- Traceability Index (T)

$T = 1 - p_{NS}$ with, p_{NS} is the proportion of unspecified refrigerants.

- Environmental Pressure Index (EPI)

$$EPI = \sum_i p_i \times (GWP_i / GWP_{max})$$

p_i is the population proportion of refrigerant i ; GWP_{max} is the maximum GWP_{100} observed.

- Ozone-Depletion Pressure Index (ODP_I)

$$ODP_I = \sum_i p_i \times ODP_i$$

ODP_i is the ozone depletion potential of refrigerant i .

- Normalised Shannon entropy (H_N)

$$H_N = [-\sum_i p_i \ln(p_i)] / \ln(k)$$

3. Results

3.1. Knowledge levels regarding refrigerants

Among the 634 participants, 67.4% ($n = 427$; 95% CI: 63.5–71.2%, Clopper–Pearson) of air-conditioner users could not identify the refrigerant in their equipment (Table 2). This proportion reached 74.0% ($n = 469$; 95% CI: 70.3–77.4%) among refrigerator users (Table 3). Weak and very weak knowledge levels accounted for 23.5% and 4.1% for air conditioners, respectively, and 18.6% and 3.5% for refrigerators. Passable and good knowledge levels remained marginal (air conditioners: 3.5% and 1.6%; refrigerators: 2.4% and 1.6%). Under the linear transformation $\text{Score} = (\text{Level} / 5) \times 100$, the distribution shown in Table 2 corresponds to a mean rescaled score of 13.56 ± 20.86 on a 100-point scale (median = 0; IQR = 0 to 40). The distribution was strongly concentrated at the lowest ordinal levels.

Table 2. Knowledge levels regarding refrigerants in air conditioners (N = 634)

Knowledge level	Observed frequency (n)	Proportion (%)	95% CI (Clopper–Pearson)
Unknown (Level 0)	427	67.4	[63.5–71.2]
Weak (Level 2)	149	23.5	[20.2–27.1]
Very weak (Level 1)	26	4.1	[2.7–5.9]
Passable (Level 3)	22	3.5	[2.2–5.2]
Good (Level 4)	10	1.6	[0.8–2.9]

Total: N = 634 (100%)

Table 3. Knowledge levels regarding refrigerants in refrigerators (N = 634)

Knowledge level	Observed frequency (n)	Proportion (%)	95% CI (Clopper–Pearson)
Unknown (Level 0)	469	74.0	[70.3–77.4]
Weak (Level 2)	118	18.6	[15.7–21.9]
Very weak (Level 1)	22	3.5	[2.2–5.2]
Passable (Level 3)	15	2.4	[1.3–3.8]
Good (Level 4)	10	1.6	[0.8–2.9]

Total: N = 634 (100%)

3.2. Variability in knowledge on refrigerant across professional groups

The Kruskal–Wallis test revealed highly significant overall differences in refrigerant knowledge across professional groups for both air conditioners ($\chi^2(4) = 427.80$, $p < 0.001$) and refrigerators ($\chi^2(4) = 369.90$, $p < 0.001$). Pearson's chi-square test also indicated a statistically significant association between refrigerant identification status and professional category ($\chi^2(4) = 47.23$, $p < 0.001$, Cramér's $V = 0.273$). These findings indicate substantial heterogeneity in refrigerant knowledge across professional groups. However, the omnibus Kruskal–Wallis tests do not identify which specific professional groups differ from one another; such pairwise differences would require appropriate post-hoc comparisons.

3.3. Knowledge structure and user profiles from PCA

Principal component analysis (PCA) conducted on four coded participant characteristics (age, technical profession, training level, and non-technical profession) identified four components. The first two components accounted for 76.43% of the total variance, with PC1 explaining 50.26% and PC2 explaining 26.16%. PC1 primarily represented a professional dimension contrasting technical and non-technical profiles, whereas PC2 represented a sociodemographic dimension characterised principally by age, with training level contributing in the opposite direction. The PCA was exploratory because the variables included continuous, binary, and ordinal measures, and the components were retained without rotation.

The numerical factor-score equations are not reproduced because the final R output used for the revised analysis provides the component structure and loadings rather than a validated set of score-equation coefficients. The variables were coded as X_1 = age, X_2 = technical profession (0/1), X_3 = training level (1–4), and X_4 = non-technical profession (0/1).

Table 4. Eigenvalues and variance explained by PCA components

Component	Eigenvalue (λ)	Variance explained (%)	Cumulative variance (%)
PC1	2.01	50.26	50.26
PC2	1.05	26.16	76.43
PC3	0.69	17.31	93.74
PC4	0.25	6.26	100.00

Table 5. Factor loadings of variables in the first two PCA components

Variable	PC1	PC2
Age (X_1)	—	0.718
Technical profession (X_2)	Dominant positive loading	—
Training level (X_3)	—	-0.688
Non-technical profession (X_4)	Dominant negative loading	—

3.4. Determinants of knowledge score: HC3 robust regression

The HC3 robust multiple linear regression model explained 41.2% of the variance in the knowledge score (OLS $R^2 = 0.412$, $N = 634$). The fitted equation for Knowledge score($\hat{Y}$) was:

$$\hat{Y} = 12.35 + 0.434 \cdot X_1 + 11.74 \cdot X_2 + 8.19 \cdot X_3$$

All three predictors were positively associated with the knowledge score: age ($\beta_1 = 0.434$, HC3 SE = 0.091, $t = 4.77$, $p < 0.001$), technical profession ($\beta_2 = 11.74$, HC3 SE = 1.97, $t = 5.96$, $p < 0.001$), and training level ($\beta_3 = 8.19$, HC3 SE = 0.88, $t = 9.31$, $p < 0.001$). The intercept ($\beta_0 = 12.35$, HC3 SE = 5.34, $t = 2.31$, $p = 0.021$) was also significant (Table 6). Holding the other variables constant, technical profession was associated with an estimated 11.74-point higher knowledge score, each additional training level with an estimated 8.19-point increase, and each additional year of age with an estimated 0.434-point increase. These are adjusted associations and should not be interpreted as causal effects. Because the predictors are measured on different scales, the raw coefficients should not be interpreted as directly comparable measures of relative predictor importance.

Table 6. HC3 robust multiple linear regression results for the knowledge score ($N = 634$)

Parameter	Coefficient (β)	HC3 Std. Error	t	p
Intercept (β_0)	12.35	5.34	2.31	0.021
Age (β_1)	0.434	0.091	4.77	< 0.001
Technical profession (β_2)	11.74	1.97	5.96	< 0.001
Training level (β_3)	8.19	0.88	9.31	< 0.001

3.5. Refrigerant use patterns in domestic refrigeration

Among the 634 participants, 74.00% (n = 469) of refrigerator users had an unspecified refrigerant, indicating low refrigerant traceability. A refrigerant was identifiable in 165 cases (26.02%). R-134a was the most prevalent identified refrigerant (15.30% of the total study population; 58.8% of identified refrigerants), followed by R-600a (5.52%; 21.2%), R-290 (2.37%; 9.1%), R-404A (1.89%; 7.3%) and R-406A (0.95%; 3.6%). R-406A, which contains HCFC-22, had a GWP₁₀₀ of 1,943 and an ODP of 0.057 (Table 7).

Table 7. Refrigerants used in refrigerators and their environmental indicators (N = 634)

Refrigerant	Observed frequency (n)	Proportion (%)	GWP ₁₀₀	ODP
Unspecified	469	74,00	—	—
R-134a	97	15,30	1 430	0
R-406A	6	0,95	1 943	0.057
R-600a (isobutane)	35	5,52	3	0
R-290 (propane)	15	2,37	3	0
R-404A	12	1,89	3 922	0

Total: N = 634 (100%)

Among the 634 air-conditioning users, the refrigerant could not be identified in 427 cases (67.4%), indicating limited refrigerant traceability and user knowledge. This lack of identification was observed among both participants who used air-conditioning equipment and those who did not. Among the 207 cases for which a refrigerant was identified, R-410A was the most frequently reported, accounting for 11.5% of the total study population, followed by R-22 (6.2%) and R-407C (6.0%). R-32 and R-404A accounted for 4.7% and 3.9%, respectively, whereas R-290 was reported only occasionally (0.3%) (Table 8). The continued presence of R-22 in air-conditioning equipment is of particular regulatory concern because this hydrochlorofluorocarbon (HCFC) has ozone-depleting properties and is subject to phase-out under the Montreal Protocol.

Table 8. Refrigerants used in air conditioners and their environmental indicators

Refrigerant	Observed frequency (n)	Proportion (%)	GWP ₁₀₀	ODP
Unspecified	427	67.4	—	—
R-410A	73	11.5	2 088	0
R-22 (HCFC)	39	6.2	1 810	0.055
R-407C	38	6.0	1 774	0
R-32	30	4.7	675	0
R-404A	25	3.9	3 922	0
R-290 (propane)	2	0.3	3	0

Total: N = 634 (100%)

3.6. Exposure profiles by sex, profession, and duration

One-way ANOVA revealed significant overall differences in equipment use duration across professional categories ($F(4, 629) = 7.52, p < 0.001$). The reported omnibus result indicates that at least one professional category differed in mean duration, but no post-hoc pairwise results are reported; therefore, specific between-category differences are not inferred here.

The Mann–Whitney U test indicated a significant sex-based difference in the knowledge score ($U = 32,847, p < 0.001$), with higher scores reported among males. A significant sex-based difference in equipment use duration was also observed ($p = 0.009$), with males reporting longer average duration. The sex distribution of the sample (male 63.2%, female 36.8%) should be considered when interpreting these comparisons. The observed differences are associations and do not establish causal effects of sex on knowledge or exposure duration (Figure 1).

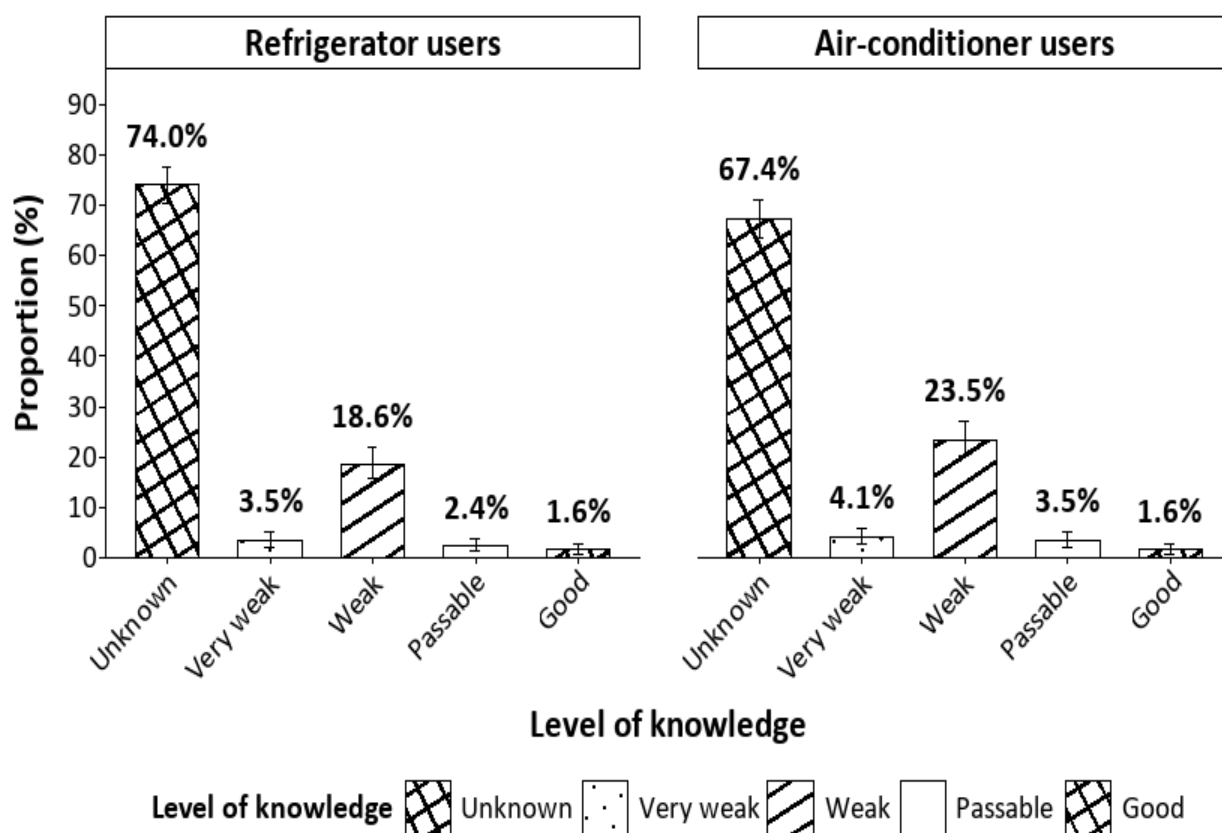


Figure 1. Distribution of users and refrigerant knowledge level

3.7. Vulnerable groups exposed to refrigerant-related risks

Based on the combined analyses, three groups may warrant particular attention in future risk-management interventions: (i) refrigeration technicians with limited training; (ii) merchants using refrigeration equipment; and (iii) households operating older refrigerators or air conditioners containing regulated refrigerants such as R-22 or R-406A. These groups are identified from the survey characteristics and refrigerant profiles; the present study did not directly measure refrigerant concentrations, leakage rates, or individual exposure.

To address the hypothesis that users of refrigeration and air-conditioning equipment have limited knowledge of the refrigerants contained in their units, a composition-based Refrigerant Traceability–Environmental Pressure Framework was applied.

3.8. Composition-based environmental indicators for air conditioners

Among the 634 air-conditioning users, a refrigerant could be identified for 207 units (32.6%), whereas the remaining 67.4% had an unspecified refrigerant. Among the identified refrigerants, R-410A was the most frequently reported ($n = 73$; 11.5% of the total study population), followed by R-22 ($n = 39$; 6.2%), R-407C ($n = 38$; 6.0%), R-32 ($n = 30$; 4.7%), R-404A ($n = 25$; 3.9%) and R-290 ($n = 2$; 0.3%). Thus, R-410A accounted for the largest proportion of identified air-conditioning refrigerants.

When refrigerant prevalence was weighted by GWP_{100} , the resulting population-level EPI was 0.164377. The largest contribution to this index was attributable to R-410A (0.061299; 37.3%), followed by R-404A (0.039432; 24.0%), R-22 (0.028389; 17.3%) and R-407C (0.027111; 16.5%). R-32 contributed 0.008144 (5.0%), whereas the contribution of R-290 was negligible at the reported precision (0.000002). Notably, R-404A had the highest GWP_{100} (3922), corresponding to the maximum reference value used for EPI normalisation, but its contribution remained lower than that of R-410A because of its lower prevalence in the study population.

For ozone-depletion potential, R-22 was the only refrigerant with a non-zero ODP (0.055) among the identified refrigerants. Its contribution to the population-level ODP_I was 0.003383, yielding an overall ODP_I of 0.003383. All other identified refrigerants had an ODP of zero and therefore made no contribution to this index. These results indicate that the environmental pressure profile was driven by different refrigerants depending on the environmental metric considered: the EPI reflected the combined effects of refrigerant prevalence and GWP_{100} , whereas ODP_I was entirely attributable to the presence of R-22 (Table 9).

Table 9. Refrigerant Distribution and Contributions to the Environmental Pressure and Ozone-Depletion Indices

Refrigerant	n	p_i	p_i (%)	GWP_{100}	GWP_i/GW P_{max}	EPI contribution	ODP	ODP contribution
R-410A	73	0.115142	11.5	2,088	0.532381	0.061299	0.000	0.000000
R-22 (HCFC)	39	0.061514	6.2	1,810	0.461499	0.028389	0.055	0.003383
R-407C	38	0.059937	6.0	1,774	0.452320	0.027111	0.000	0.000000
R-32	30	0.047319	4.7	675	0.172106	0.008144	0.000	0.000000

R-404A	25	0.039432	3.9	3,922	1.000000	0.039432	0.000	0.000000
R-290 (propane)	2	0.003155	0.3	3	0.000765	0.000002	0.000	0.000000
Total identified	207	0.326498	32.6	—	—	0.164377	—	0.003383

N = 634 air-conditioning units; unspecified cases = 427; $p_{NS} = 427/634 = 0.673502 = 67.4\%$; GWP_{max} = 3,922, corresponding to R-404A; Traceability Index $T = 1 - 0.673502 = 0.326498 = 32.6\%$.

3.8.1. Traceability and distributional heterogeneity

The quantitative assessment showed low refrigerant traceability among air-conditioning units. The Traceability Index (T) was 0.3265 (32.6%), indicating that refrigerants were identified for approximately one-third of the units, while 67.4% remained unspecified. The Shannon entropy was 1.1453, corresponding to a normalised entropy (H_N) of 0.5886. This value indicates moderate distributional heterogeneity across the seven categories considered, including the unspecified category. Overall, the indices demonstrate a substantial gap in refrigerant identification alongside a moderately heterogeneous refrigerant distribution.

The key finding is that refrigerant traceability is markedly limited: only 32.6% of equipment had an identified refrigerant, leaving 67.4% of the study population without identifiable refrigerant information. This substantial information gap coexists with a moderately heterogeneous distribution of the refrigerants reported ($H_N = 0.5886$).

3.8.2. Refrigerant-specific contributions to the EPI and ODP

R-410A contributed the largest share of the population-level EPI (37.3%), followed by R-404A (24.0%), R-22 (17.3%) and R-407C (16.5%). R-32 contributed 5.0%, whereas the contribution of R-290 was negligible at the reported precision. These calculations are based on the frequencies and GWP100/ODP values reported in Table 8. The principal finding was that R-410A was the largest contributor to the composition-based climate indicator, whereas R-22 was the sole contributor to the observed ozone-depletion indicator (Table 10).

Table 10. Interpretation of the EPI contributions

Refrigerant	EPI contribution	Contribution to total population-level EPI (%)	ODP	ODP contribution
R-410A (HFC)	0.061299	37.3	0	0
R-22 (HCFC)	0.028389	17.3	0.055	0.003383

R-407C (HFC)	0.027111	16.5	0	0
R-32 (HFC)	0.008144	5.0	0	0
R-404A (HFC)	0.039432	24.0	0	0
R-290 (HC)	0.000002	0.0	0	0
Total	0.164377	100.0	—	0.003383

4. Discussion

4.1. Refrigerant knowledge gap and refrigerant management

The present findings reveal a substantial refrigerant knowledge gap, with 67.4% of air-conditioning users and 74.0% of refrigerator users unable to identify the refrigerant contained in their equipment. This finding is consistent with previous evidence that access to technical information is influenced by education, occupation and exposure to refrigeration technologies (UNEP, 2023; Velders et al., 2015; Andersen and Sarma, 2012). Limited access to technical training and incomplete equipment labelling may contribute to this information deficit in settings where refrigeration services are partly delivered through informal markets (UNEP DTIE OzonAction, 2019).

Knowledge and refrigerant traceability are complementary but distinct aspects of refrigerant information management. Knowledge concerns users' ability to recognise and understand refrigerants, whereas traceability depends on the availability of reliable information identifying and documenting refrigerants throughout the equipment life cycle. Previous studies reported limited refrigerant knowledge among consumers and technicians and highlighted the importance of labelling, training and accessible technical information (Martinho et al., 2022, 2023). Effective traceability also requires systematic recording of refrigerant identity, inventory, recovery and handling across stakeholders, supported by appropriate management systems (Hamasaki et al., 2025; Nomura and Kato, 2025). In the present study, the high proportion of unspecified refrigerants (67.4% in air conditioners and 74.0% in refrigerators) coincided with predominantly low knowledge levels, suggesting a broader information gap. However, because the individual association between knowledge and refrigerant identification only was not directly tested, this relationship should be interpreted as conceptual and descriptive rather than causal.

4.2. Professional and training factors associated with knowledge

The PCA provided complementary evidence on the structure of participant profiles. The first two components accounted for 76.43% of the total variance, with PC1 reflecting a professional contrast between technical and non-technical profiles and PC2 reflecting a predominantly age-related sociodemographic dimension, with training level contributing in the opposite direction. These components should be interpreted as exploratory dimensions of the observed participant characteristics rather than as validated latent constructs. The HC3-robust regression explained 41.2% of the variance in the knowledge score (OLS $R^2 = 0.412$), and age, technical profession, and training level were each positively associated with the score. The convergence between the PCA structure and regression results indicates that professional and training characteristics are important dimensions of the observed knowledge distribution, while the regression additionally shows an independent positive association with age after adjustment for the other predictors.

4.3. Composition-based environmental indicators

The composition-based analysis provides an additional dimension to the assessment of users' knowledge by quantifying the traceability of refrigerants and characterising the environmental structure of the refrigerant distribution. In the present study, 67.4% of the surveyed equipment had no identifiable refrigerant, corresponding to a low Traceability Index ($T = 0.326$). Taken together with the questionnaire-based assessment of refrigerant knowledge, this finding supports the hypothesis that users of refrigeration and air-conditioning equipment are insufficiently informed about the refrigerants contained in their units. Importantly, the traceability analysis adds an operational dimension to this finding: it shows not only that knowledge is limited, but also that the identity of the refrigerants present in a substantial proportion of equipment cannot be reliably established from the information available at the user level.

This result is consistent with previous studies showing that information concerning refrigerants remains insufficient among both consumers and refrigeration professionals. In a survey of 648 consumers in Portugal, Spain and France, Martinho et al. (2022) reported limited information concerning the type of refrigerant used in domestic equipment and the technicians authorised to install or maintain such systems. The authors also observed that the type and quantity of refrigerant were rarely considered in equipment-purchasing decisions, despite consumers attributing substantial importance to environmental risks associated with refrigeration gases. Similarly, a subsequent survey of 586 refrigeration technicians found that their knowledge of

fluorinated gases was lower than expected and highlighted the need for more effective information and training programmes (Martinho et al., 2023). The present findings therefore extend previous evidence by translating this information deficit into a measurable population-level traceability indicator rather than relying solely on perceived knowledge or reported behaviour.

The environmental indices further show why this information gap matters for refrigerant management. The composition-based EPI (0.164) indicates that the environmental profile of the identified refrigerants cannot be inferred from prevalence alone, because refrigerants with markedly different GWP_{100} values coexist within the study population. This is particularly relevant for R-410A and R-404A, which have comparatively high GWP values, whereas R-22 combines a substantial GWP with a non-zero ODP. Previous reviews have emphasised that refrigerant selection involves simultaneous consideration of climate impact and ozone-depletion characteristics, and that the transition towards lower-impact alternatives remains technically and environmentally complex (Bolaji and Huan, 2013; Yang et al., 2021). The present framework therefore provides a compact way of linking the information dimension of refrigerant identification with the environmental characteristics of the refrigerant mixture observed in the population.

The ODP_{I} value (0.0034) adds a distinct ozone-related dimension to this assessment. Its contribution was entirely attributable to R-22, consistent with the recognised non-zero ozone-depletion potential of HCFC-22, whereas the HFCs considered in the study have zero ODP. R-22 has also remained an important refrigerant. The two indicators capture different environmental dimensions and may therefore identify different priorities within the same equipment population.

Finally, the normalised Shannon entropy ($H_N = 0.589$) indicates moderate heterogeneity in the seven-category refrigerant distribution. Shannon entropy is appropriate for describing the information content or heterogeneity of a categorical distribution, although its interpretation should remain distinct from that of a direct knowledge score (Shannon, 1948; Jost, 2006). The central challenge revealed by this study is not refrigerant diversity per se, but the widespread inability to identify the substance present in each unit. This traceability gap has direct consequences for end-of-life management, since safe recovery, decommissioning, and disposal all require prior knowledge of the refrigerant type; its absence elevates the risk of improper handling and uncontrolled release. Compounded by the technical knowledge gaps

documented here, these findings point to a dual priority, namely improving refrigerant traceability and strengthening technician training, in line with the evidence that skills and training are critical determinants of refrigerant management quality (Koronaki et al., 2012).

4.4. Occupational and public-health considerations

Chlorofluorinated and hydrofluorinated refrigerants can reach asphyxiating concentrations in the event of leakage in confined spaces. Also, repeated exposure has been, indeed, associated with cardiovascular and hepatic effects (Calm, 1996). Flammable natural refrigerants such as R-290 and R-600a additionally pose explosion risks in enclosed spaces. The refrigeration technicians identified as an at-risk group in this study frequently handle these substances without adequate personal protective equipment, owing to limited training and resources. Strengthening occupational safety measures, including provision of protective equipment, safe-handling training, and leak-detection systems, should therefore be considered a public-health priority in Togo.

The environmental analysis revealed a heterogeneous refrigerant profile. In refrigerators, R-134a was the most frequently identified refrigerant (15.30% of the total study population), whereas R-600a and R-290 accounted for 5.52% and 2.37%, respectively. R-134a has a substantially higher GWP100 than these hydrocarbon refrigerants, so its prevalence should not be interpreted as evidence of a low-impact refrigerant transition. In air conditioners, R-410A was the most frequently identified refrigerant, while R-22 remained present in 6.2% of units and R-32 accounted for 4.7%. R-406A was identified in 0.95% of refrigerators and had a non-zero ODP. These findings demonstrate coexistence of refrigerants with markedly different climate and ozone-related characteristics rather than providing direct evidence of actual emissions or equipment non-compliance.

The identification of potentially vulnerable groups has implications for environmental-health risk management, but the present survey did not directly measure occupational exposure, leakage, personal protective equipment use, or thermal-decomposition products. Accordingly, the findings should be interpreted as identifying groups for targeted information and future exposure assessment rather than as demonstrating increased exposure or toxicity in these groups.

4.5. Limitations of the study

Overall, this analysis supports the presence of limited refrigerant information among users while providing a complementary quantitative characterisation of refrigerant composition. Its principal contribution is not to estimate actual refrigerant emissions, but to quantify the coexistence of an information deficit, traceability limitation and composition-based environmental indicators. Because equipment charge sizes, leakage rates, service histories and measured atmospheric concentrations were not available, the EPI and ODP_I should be interpreted as composition-based population indicators rather than estimates of atmospheric emissions or absolute environmental impacts.

The composition-based EPI and ODP_I analyses were performed for air conditioners because access to refrigerators for recording refrigerant quantities was limited. The refrigerator analysis was therefore restricted to refrigerant identification, composition and reported GWP100/ODP characteristics.

5. Conclusion

This study provides a multicity assessment of refrigerant knowledge and usage patterns among refrigeration and air-conditioning equipment users in Togo. The findings reveal a substantial information deficit, with 67.4% of air-conditioning users and 74.0% of refrigerator users unable to identify the refrigerant in their equipment. The PCA showed that the first two components accounted for 76.43% of the variance, with a principal professional contrast between technical and non-technical profiles and a complementary age-related dimension. Technical profession, training level and age were positively associated with the knowledge score in the HC3-robust regression, which explained 41.2% of its variance (OLS R^2). Among refrigerators, R-134a was the most frequently identified refrigerant (15.30% of the total study population), while R-22 remained present in 6.2% of air conditioners and R-406A in 0.95% of refrigerators. For air conditioners, the composition-based EPI was 0.164377; R-410A contributed 37.3% of this indicator and R-22 accounted for all observed ozone-depletion pressure. The findings support improved equipment labelling, technical training, refrigerant traceability and enforcement of existing refrigerant-management requirements. Future studies should directly measure refrigerant charge sizes, leakage rates and occupational exposure to enable emission and risk estimates beyond the composition-based indicators reported here.

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